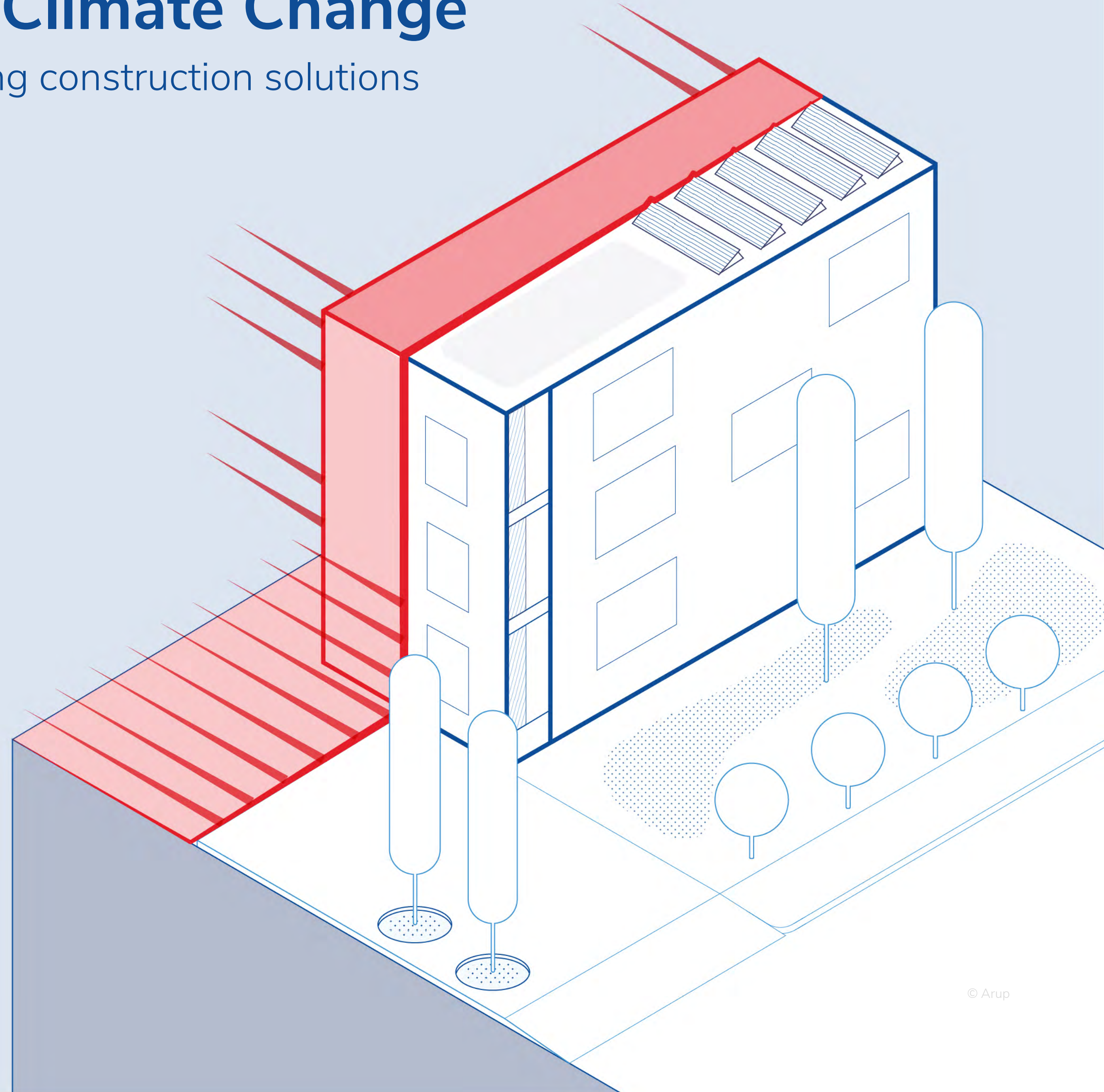
Adapting Buildings to Climate Change

Insights into the contribution of building construction solutions to the climate adaptation agenda



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Content

Summary:
Adapting Buildings to Climate Change

Summary:
Introduction

Designing and retrofitting buildings to withstand future climate impacts is a global priority. The technical capacity exists, and the need is urgent for the billions of people who live and work in them, for economies, and for communities. Building construction solutions and their value-chain can offer a distinctive contribution for adapting to future climates.

Since 2000, more than 7000 disasters have occurred globally, affecting people, economies, and buildings. Every additional 0.5°C of global warming may cause discernible increases in the intensity and frquency of extreme events. Buildings are also affected in quieter but transformative ways: rising average temperatures make them inhospitable and drive-up energy demand; water stress and drought impose restrictions; and buildings themselves contribute to local heat through the urban heat island effect. By all accounts, this calls for urgent, collective, large-scale action for both existing and new buildings.

Fortunately, technical building solutions and capable players exist globally with the capacity to respond. But these challenges cannot be met through a top-down action delivered in silos.

Adaptation requires a process that is supported by updated regulation, more accessible climate data and the capacity to interpret them, and finance.

One dimension of this landscape with potential to advance the adaptation agenda is the construction solutions sector that devise, specify, distribute and use building products and systems. This can leverage a broad spectrum of solutions, from time-tested, affordable approaches used for centuries, to cutting-edge innovations now being applied, and ideas yet to be developed or validated.

The purpose of this document is to offer insights into this specific dimension and the contributions that products and systems can make toward addressing the most pressing climate concerns. Insights are drawn from three regions — the United States in North America, Spain in Europe, and India in South Asia. Though not comprehensive of global diversity, these regions represent an interesting range of approaches, market maturity, and geographic contexts

The ambition of this report is to contribute meaningful insights to the global debate and to raise awareness among stakeholders in the built environment about opportunities to advance the climate agenda. It is intended as a contribution to the ongoing global discussion and does not claim to be exhaustive or normative in this complex and evolving field and existing tensions and challenges are acknowledged. It is not a guidance document and should not be used as such.

The document first introduces key facts that support the need for urgent climate adaptation of buildings, at scale and complementing progress made on decarbonising buildings. It then illustrates ways in which the current design practice is striving to integrate climate uncertainty into workflows. Finally, it proposes a taxonomy of solutions involving materials, systems and product that contribute to address key climate hazards such as heat waves and extreme temperatures, wildfires, flood and heavy rain, extreme winds and storms.

Summary:
Key Takeaways for Action

1. ↗

The adaptation imperative

Climate change is the defining challenge for the built environment. We must adapt existing building stock while rethinking how we design new buildings.
It is not only about what we build, but how, and with what sensibility we respond to both sudden shocks and persistent climate transformations.

2. ↗

A dual relationship with climate

Buildings must withstand both acute events — such as extreme winds, storms, wildfires, and floods — and chronic pressures, including the global rise in average temperatures. While new and existing buildings must find ways to cope with a changing climate, they also have a responsibility to mitigate their own contribution to urban heat island effects in cities. This dual relationship with the climate calls for a fundamental rethinking of how buildings are conceived, designed, and managed.

3. ↗

A challenge of scale

Designing new buildings to the negative observed and expected effects of climate change is crucial: capacities exist and codes are slowly but steadily evolving to enable that. It is also critical to engage on retrofitting of the existing buildings, which in some regions of the world represents the 90% of the stock.

4. ↗

Complementary design strategies

Climate adaptation can be achieved through a mixed approach of robustness, adaptiveness and flexibility Designers can adopt complementary strategies to address a variety of climate hazards, design objectives and solutions adopted that balance KPIs and allow for light and sustainable construction to coexist with resilience needs.

5. ↗

Pathways to adaptive design

Multiple techniques and methods are being applied in the design workflow and retrofitting practice to understand and manage present and future risk. This includes risk analytics, rethinking architectural relationship with the environment, updating data with climate models, adopting adaptive technologies and unlocking the power of digital.

6. ↗

Evolving building codes and risk transfer

Building codes are gradually integrating climate change considerations, although at a measured pace that reflects both the complexity and the costs involved. The case for transferring some of the risks that cannot be meaningfully designed out or mitigated is also growing, although to different extents and maturity across the world.

7. ↗

A growing market for adaptation

There is an opportunity for investment in climate adaptation. Today, the construction solutions' sector is moving towards developing hazard-specific products, enhancing performances of existing solutions, or repositioning them as hazard-focused measures. These products and systems are available and often affordable worldwide, from Europe to India to the US, but their value is realized only when they are strategically applied to specific climate risks.

8. ↗

Performance and integrated systems

Performance-driven solutions exist currently to advance adaptation in buildings. This evolution reflects a shift from isolated products to integrated, performance-based systems (i.e. assemblies of products and components) designed to address the challenges posed by dynamic climate conditions and multiple hazards in an coordinated fashion.

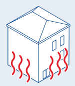
9. ↗

Envelope and site as "the first lines of defense"

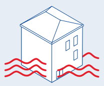
Climate adaptive solutions extend across the building envelope and its immediate surroundings, offer the first line of defense against climate stresses through products and systems designed and engineered for robustness, adaptability, and flexibility.

Summary:
Key Takeaways for Action

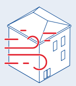
Main Hazards



Heat waves and extreme temperatures



Flood and heavy rain



Extreme winds, storms

Wildfires

Climate adaptive solutions

A – Thermal Envelope Systems

Managing the chronic increment of temperatures

Thermal envelope systems, such as insulation panels, thermal inertia walls, insulated glass units, stabilize indoor temperatures, reduce buildings energy demand, and improve comfort. Their effectiveness depends on holistic design, integrating insulation with ventilation, solar protection, and moisture control to avoid maladaptation. These systems could offer co-benefits: improved acoustic insulation, fire performances, and reduced water permeability that enhance resilience to wildfires and heavy rain.

B – Solar protection Systems

The universal need for solar protection

Solar protection systems reduce solar heat gain while preserving natural light. Applied to glazed surfaces and outdoor areas, they work in coordination with thermal envelope systems to improve energy efficiency in warm climates and cope with extreme temperatures and heat waves. Solar protection is needed everywhere, even in historically cool cities, through solar shading strategies, solar control glazing, and site-level canopies or tensile structures.

C – Green building envelopes and green infrastructure

Beyond aesthetics: green infrastructures as an essential

Investment in green infrastructures is no longer architectural decoration but essential for reducing Urban Heat Island effects and providing Sustainable Urban Drainage Systems (SuDS) benefits through stormwater retention. Plants and soil absorb CO_2, purify air, and reduce noise throughout their lifespan. Green roofs and facades lower energy consumption in buildings by naturally insulating, shading surfaces from direct sunlight and enhancing evapotranspiration to dissipate heat and stabilize indoor temperatures.

D – Heat-Reflective and Stormwater-Permeable Surfaces

Surface solutions for microclimate management

Surfaces of the building envelope and of outdoor surroundings could help manage microclimate and urban hydrology: light-colored or reflective products reduce Urban Heat Island effects, while permeable surfaces mitigate flood risks during heavy rain, support Sustainable Urban Drainage Systems (SuDS) and help replenish aquifers.

E – Enhanced-resistance protective system

Climate resistance through integrated construction systems

Climate adaptive solutions require enhanced resistance to withstand wildfires, heavy rains, floods, hail, extreme winds, and storms. These solutions are often pre-tested and certified for durability and reliability. However, the performance of high-resistance products depends not only on their inherent properties but also on their interaction with all the other building components.Particular attention must be paid to fixings and fastening systems, with coordinated detailing to ensure that fire, water, and impact protection work together effectively.

Summary:
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Summary:
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References

Units

The units of measurement are in the International System (SI).

Bibliography

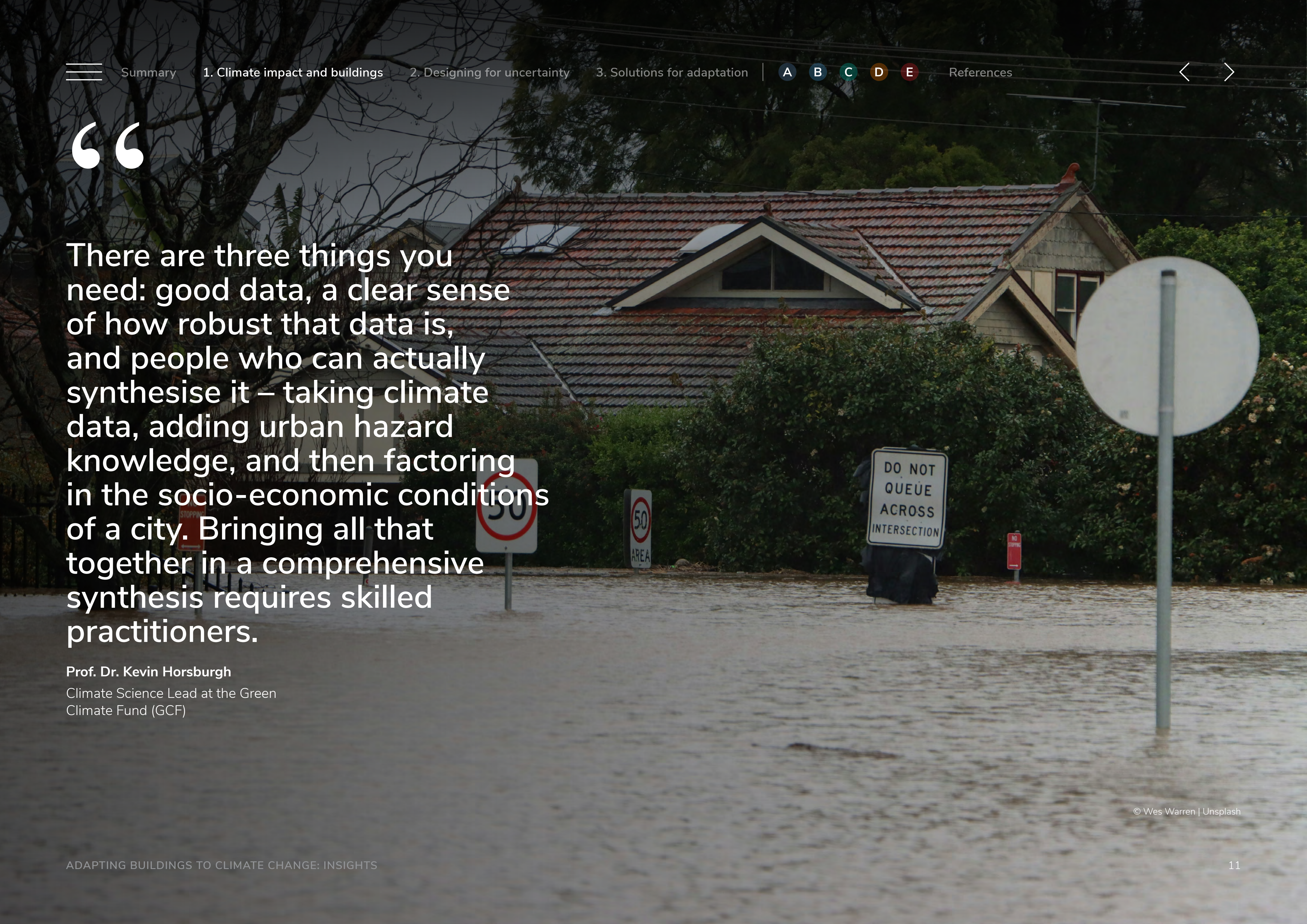
Figures, data and facts mentioned in the report have been researched and checked for accuracy using reputed professional or academic literature. For ease of consultation, however, all references have not been provided in-line but have been collated in the final chapter, with cross-reference to key figures, facts and findings listed in the report, whenever relevant.

Mention

Arup & Saint-Gobain (2026) Adapting Buildings to Climate Change: Insights into the contribution of building construction solutions to the climate adaptation agenda.

Climate impact and buildings: Insights on why buildings need to adapt fast

1



> “There are three things you need: good data, a clear sense of how robust that data is, and people who can actually synthesise it – taking climate data, adding urban hazard knowledge, and then factoring in the socio-economic conditions of a city. Bringing all that together in a comprehensive synthesis requires skilled practitioners.

Prof. Dr. Kevin Horsburgh
Climate Science Lead at the Green Climate Fund (GCF)

Climate impact and buildings:
Insights on why buildings need to adapt fast

Climate change is affecting all sectors of society. This chapter presents why buildings should adapt urgently and at-scale.

- Climate change has already changed with significant impact for buildings
- Future changes in climate will create a surge in hazards such as floods, extreme temperatures and winds
- Adapting both new and existing building stock to a deal with extremes and changing climate is a priority

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Climate impact and buildings:
Insights on why buildings need to adapt fast

Climate change is already here and will continue into the 21st Century. Global temperatures have already risen above 1°C relative to pre-industrial levels, with further warming expected across all future scenarios.

Environments and risk profiles have shifted worldwide, as a consequence of climate change. Silent, transformational changes have occurred alongside increasingly destructive forces —both critical for buildings we construct and inhabit.

Consensus that climate change is *unequivocally* the result of human activity has been established by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6, 2021–2022) upon gradual build-up in confidence in previous ARs. The atmosphere, ocean, and land have warmed: each of the last four decades has been successively warmer than any since 1850, with the rate of warming accelerating especially in the past 50 years. By 2011–2020, global surface temperatures had warmed by approximately 1.1°C above pre-industrial levels, according to the AR6. In 2024, for the first time average global temperature exceeded +1.5°C with respect to pre-industrial levels. Europe and North America have experienced warming rates above the global average, while India's average temperature has increased by approximately 0.7°C since the early 20th century.

Climate transformation is gradual and often invisible, making climate change a "perfect" problem—intangible and perceived as distant. Yet shifts in thermal conditions affect buildings and energy demand, while changes in temperature, rainfall, and moisture have altered climate extremes, shifted statistical return periods, and increased variability. More intense hazards—including floods, heavy rainfall, extreme winds, temperature extremes, and drought—have been attributed to climate change with high confidence.

>> Climate change has altered baseline conditions for building design, construction, and management. Intensified extremes are conspicuous threats, but gradual shifts in thermal and moisture regimes present less visible, yet critical, long-term risks.

Climate impact and buildings:
Insights on why buildings need to adapt fast

Climate will continue to change, well into the future

Even with the most aggressive mitigation policies, Earth system-inertia means that further warming and its impacts are already locked in for decades to come. Advanced climate models—including those from the Coupled Model Intercomparison Project Phase 6 (CMIP6)—along with scenario frameworks such as the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), consistently project ongoing changes that might reshape the environmental context in which the built environment operates.

Key takeaways include:

1.

Precipitation Pattern Shifts

- Accelerating water cycle. Global precipitation increases progressively under both scenarios, with SSP5-8.5 showing greater precipitation increase by 2100 with respect to SSP2-4.5.
- High uncertainty in precipitation projections for water resources. However, precipitation projections show substantial uncertainty ranges in global/land precipitation changes across SSP scenarios.
- Regional disparities masked – or the climate change paradox. Global averages conceal critical regional patterns where some may areas suffer intense droughts, while others could see devastating floods.

2.

Scientific Confidence Levels

- High confidence in temperature. Projections based on different climate models with 90% confidence intervals for temperature changes.
- Moderate confidence in precipitation. Uncertainty ranges reflect complex regional interactions and feedback mechanisms in the global water cycle.
- IPCC AR6 authority. These projections may represent the most comprehensive assessment in climate science, incorporating the latest CMIP6 model ensemble.

3.

Critical Temperature Thresholds

- Mid-century convergence. Both moderate and high-emission scenarios might show similar temperature rises around mid-century, suggesting some climate impacts are largely committed regardless of near-term emission pathways.
- Dangerous divergence. High-emission futures could lead to substantially greater warming by 2100 compared to moderate ones, which highlights the potential of mitigation to limit risks.

4.

Timeline for Climate Action

- Immediate action window. The 2020s are critical for determining which trajectory we follow, as both scenarios show similar impacts through 2050.
- Compound acceleration could emerge post-2050. Climate impacts could intensify non-linearly, with high-emission pathways potentially driving sharper rises in temperature alongside greater precipitation swings.
- Irreversible commitments. Decitions made this decade might shape climate conditions for the rest of the century.

5.

Policy and Planning Implications

- Adaptation urgency. Even under moderate scenarios, significant climate adaptation is required by mid-century.
- Mitigation effectiveness. Scenario differences by 2100 suggest aggressive emission cuts may dramatically limit warming and risks.
- Infrastructure planning. Near-term commitments could push conditions beyond 2°C mid-century, so resilient infrastructure may require adaptability for greater risks under delayed mitigation.
- The built environment is significantly affected by climate change impacts from changes in climate conditions and extreme weather events.

Understanding regional variations of climate change

Europe

In **Northern Europe**, climate impact-drivers could shift towards generally hotter conditions with wetter extremes, including heavier precipitation events. Western and Central Europe may become hotter and see more frequent or intense wet extremes, with parts of this region additionally exposed to increased fire-weather conditions.

The Mediterranean area could become hotter and drier overall, even though some areas may experience more intense heavy-rainfall events and associated flood risks. Across the European continent, increase in Tropical cyclones intensity or extreme winds may also be experienced.

India

India and the surrounding South Asian land regions, could become hotter. Many areas could also experience wetter extremes, including heavier precipitation events, with potentially flooding associated events

North America

North America could become generally hotter, with many regions also seeing increases in wet extremes such as heavy precipitation events, though patterns vary significantly across the continent.

Along the western coastal and interior regions, conditions could shift toward hotter and drier climates, with elevated fire-weather risk, even as some areas also face more intense extreme rainfall episodes. Tropical cyclones intensity or extreme winds may also be experienced in some sub-regions.

Regional variations of climatic impact drivers. This page presents a summary of potential patterns of changes in temperature, precipitation, and other climatic impact-drivers (CIDs) by around 2050 under approximately ~2°C of global warming for the three target regions of this study.

Summary: Arup (2026); based on data by IPCC WGI AR6 (2021).

Understanding climate scenarios

The Representative Concentration Pathways (RCPs) describe possible trajectories of greenhouse gas concentrations, land-use change, and resulting radiative forcing (in W/m²) projected for the 21st century. Radiative forcing measures the change in the Earth's energy balance due to these drivers. Different RCPs correspond to different levels of warming depending on societal actions: for example, RCP8.5 represents ~8.5 W/m² by 2100, historically used in risk assessments as a high-end scenario, projecting global mean temperature increases of roughly 4–5°C. Though unlikely, concentration of 8.5 W/m² would lead to very significant effects on climate systems.

The IPCC's Sixth Assessment Report (AR6) introduced Shared Socioeconomic Pathways (SSPs), which outline five possible global development trajectories — sustainable development (SSP1), middle-of-the-road (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fuelled development (SSP5) — that influence future emissions and therefore which RCPs may be realized. Combining SSPs and RCPs provides an integrated framework to assess future climate risks, accounting for both physical climate changes and socioeconomic contexts.

>> The potential implications of the different SSP-RCP combinations for the end of the century are summarized below. Our current trajectory seems to lie between SSP2-4.5 and SSP3-7.0.

SSP1-RCP1.9

Is the most optimistic IPCC scenario linked to limiting warming to 1.5 °C, increasingly unlikely under current policies without very rapid and deep emission cuts

- It assumes that Global GHG and CO_2 emissions might drop to net zero around 2050
- By 2100, the global average annual temperature may have increased by up to 1.4°

SSP1-RCP2.6

Is still possible but only with deep reductions in CO_2 and other greenhouse gas emissions in the coming decades

- It assumes that global GHG and CO_2 emission decline to net zero around 2070
- By 2100, the global average annual temperature increase might be up to 1.8°

SSP2-RCP4.5

Is a possible scenario, but relies on current national and international commitments being achieved

- It assumes that GHG emissions could hover up to current levels and then decline around mid-century
- By 2100, global average annual temperatures could rise by up to 2.7°

SSP3-RCP7.0

Is a high-emissions pathway broadly consistent with current trends. This could align with ongoing trends if emissions continue to increase.

- It assumes that emissions might roughly double by 2100
- By 2100, the average annual temperature increase might be up to 3.6°C

SSP5-RCP8.5

Is a possible, yet pessimistic scenario, if global socio-economic pathways deteriorate and emissions increase at an accelerated rate

- It assumes that rapid rises could double emissions by 2050
- By 2100, the annual temperature increase might be up to 4.4°C

Climate impact and buildings:
Insights on why buildings need to adapt fast

Climate hazards have become more intense and frequent as a result of global warming. Each additional °C of warming could increase the likelihood and severity of extreme weather events and environmental transformations.

Changes in key temperature and precipitation parameters have significantly altered global hazard profiles. Intensifying extreme winds, temperatures, flood and heavy rain will influence the built environment in the decades to come.

Attribution science establishes that anthropogenic climate change is measurably altering the frequency, intensity, and spatial distribution of extreme weather events. These changes stem from both thermodynamic factors—the increased energy and moisture content of a warmer atmosphere—and dynamic factors that shape circulation patterns and storm behaviour. The relationship between global warming and hydrometeorological extremes is nonlinear: even relatively small shifts in global mean temperature can produce discernible changes in the tails of climate distributions yielding disproportionate increases in the intensity, frequency, and persistence of heat extremes.

For precipitation-driven and compound hazards, a distinct mechanism operates. Under Clausius–Clapeyron scaling, the atmosphere's moisture-holding capacity rises by ≈7% per 1°C of warming. That added moisture increases latent heat release and storm energetics, amplifying short-duration rainfall, surface runoff, and the likelihood of compound events (for example, extreme precipitation coinciding with saturated soils or coastal surge). These processes underlie observed increases in heavy rainfall and flood potential, while regional outcomes remain governed by circulation changes and land–atmosphere feedbacks that are still under study. Taken together, these mechanisms are accelerating key hazard drivers—water, wind, heat, and soil—producing both acute risks (heatwaves, floods, droughts, wildfires, storms) and chronic stresses (altered precipitation regimes, sea-level rise, soil degradation).

In this context, floods, heat waves, and heavy rains are likely to dominate the climate risk landscape for buildings through 2050, as well as extreme winds events although links between climate change and these events are less clear. These four hazards have high geographic spread, building-specific vulnerabilities, and cumulative economic impacts. Between 1980–2023 in Europe, hydrological hazards (floods) accounted for around 45–50% and meteorological hazards (storms) for around 25–30% of total climate-related economic losses, while heatwaves contributed roughly 15–20% but account for 95% of climate-related fatalities, and severely stress building systems – raising cooling demand, overloading MEP systems, and degrading product performance.

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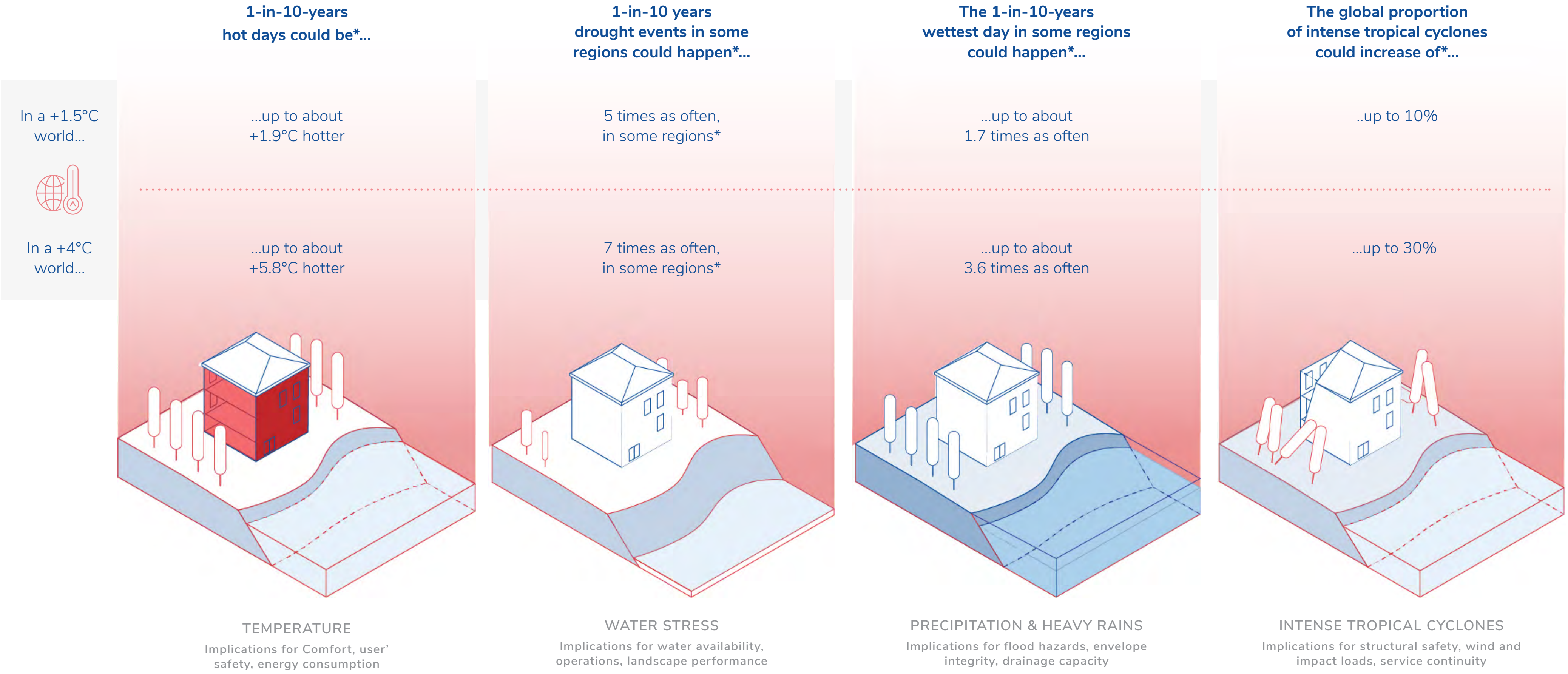
Additional hazards – though less spatially dominant – remain material. In 2020, 6.2 million U.S. properties were hit by damaging hail, causing ~$14.2 billion in losses. Wildfires have destroyed ~130,000 structures across two decades; the 2025 Los Angeles fires alone razed over 16,000 structures, generating an estimated $76-$131 billion in property and capital losses. Droughts, while not causing structural failure, create operational and user safety issues. In Europe, drought frequency is projected to double over 25% of the Mediterranean and 15% of the Atlantic region under 3°C warming. Two-year drought events may rise sevenfold by 2051–2100. In India, drought-prone areas have expanded by 57% since 1997. These trends raise serious concerns for service continuity in large public buildings and escalate competition for water in urban zones.

Context-specific adaptation is imperative. Europe, North America, and India exemplify the sharp regional escalation of climate hazards with each region experiencing unique but intensifying extremes due to the interplay of warming with local geography, atmospheric circulation, land use, and ecosystem characteristics. In Europe, the frequency of 1-in-100-year heatwaves has already increased to once every 20 years and could occur every five years or less under RCP8.5, with the decade 2011–2021 recording unprecedented numbers of heatwave events, notably in 2003, 2007, 2012, 2015, and 2018.

In the United States days with heat index above 40°C are projected to triple, which might affect a large portion of the population. India is projected to see an eightfold increase in days over 35°C by 2100 - rising from 5.1 annually in 2010 to 42.8 under a high-emissions scenario (RCP 8.5 / SSP5-8.5). Several major cities such as Mumbai and Delhi are projected to experience a twofold rise in heatwave days by 2030.

>> Floods, heatwaves, extreme precipitation, and winds are critical hazards that may become increasingly prevalent globally. Hail and wildfires, while geographically less widespread, still pose material risks. Droughts and rising mean temperatures will continue to influence building design, construction, and operations, even if they lack abrupt destructive forces. Given the established link between anthropogenic climate change and the intensification of hazards, proactive adaptation is essential.

> **Hurricane and tornado / thunder (hail) storms are currently first and second as the biggest risk categories for insurance companies in the US. Wildfire risk is rapidly increasing in the West as are coastal and riverine flooding across the entirety of North America. Cyclones are a concern in India, such as windstorms in Europe. Heatwaves and drought are increasing concern, especially in hot climates.**
>
> Lucas J. Hamilton, Saint-Gobain



Climate futures: effects of climate change on key environmental parameters relevant to building siting, design and operations. The response of the climate system relative to 1850–1900 illustrates why the built environment must adapt to multiple, interacting climate pressures. Different levels of global warming in °C can drive substantial changes in key climate parameters and extremes. For example, in a world that is +1.5 °C warmer than pre-industrial levels, the global proportion of intense tropical cyclones could increase significantly, which increase the need for resilient design. These shifts have direct implications for planning, siting, design and operation of buildings and infrastructure. (Image: Arup (2026); based on data from IPCC AR6 WGI (2021)).

*Upper bounds of the possible ranges are shown here: future climate is inherently uncertain, and this uncertainty is itself a core challenge for the built environment.

Climate impact and buildings:
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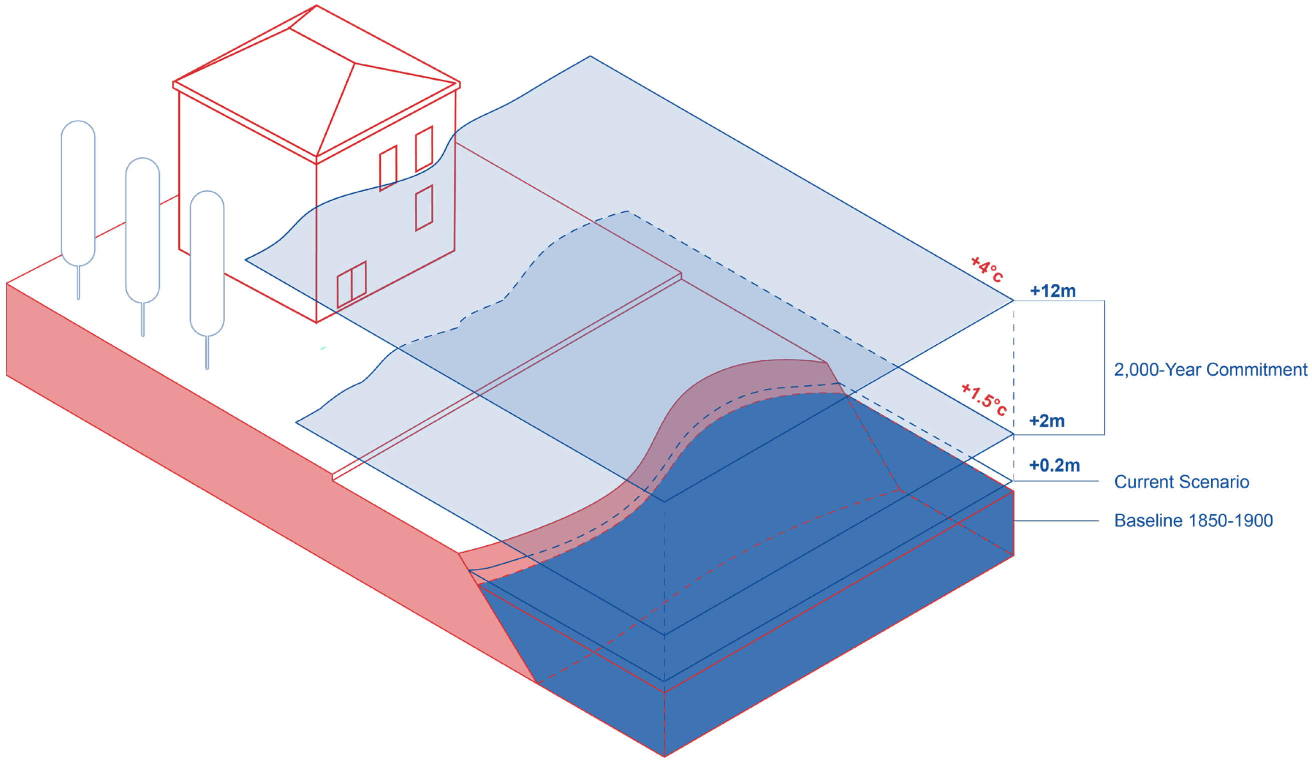
Long-term consequences: Sea level rise

According to the IPCC sea level has already increased by 20 cm and may continue to increase in the future depending on emissions and other factors. As the sea reacts slowly to warming, we may expect that sea-level will continue throughout this century, and possibly for thousands of years. Whereas very long timeframes are difficult to grasp for our society, relatively short-term implications for coastal cities need to be understood and addressed urgently.

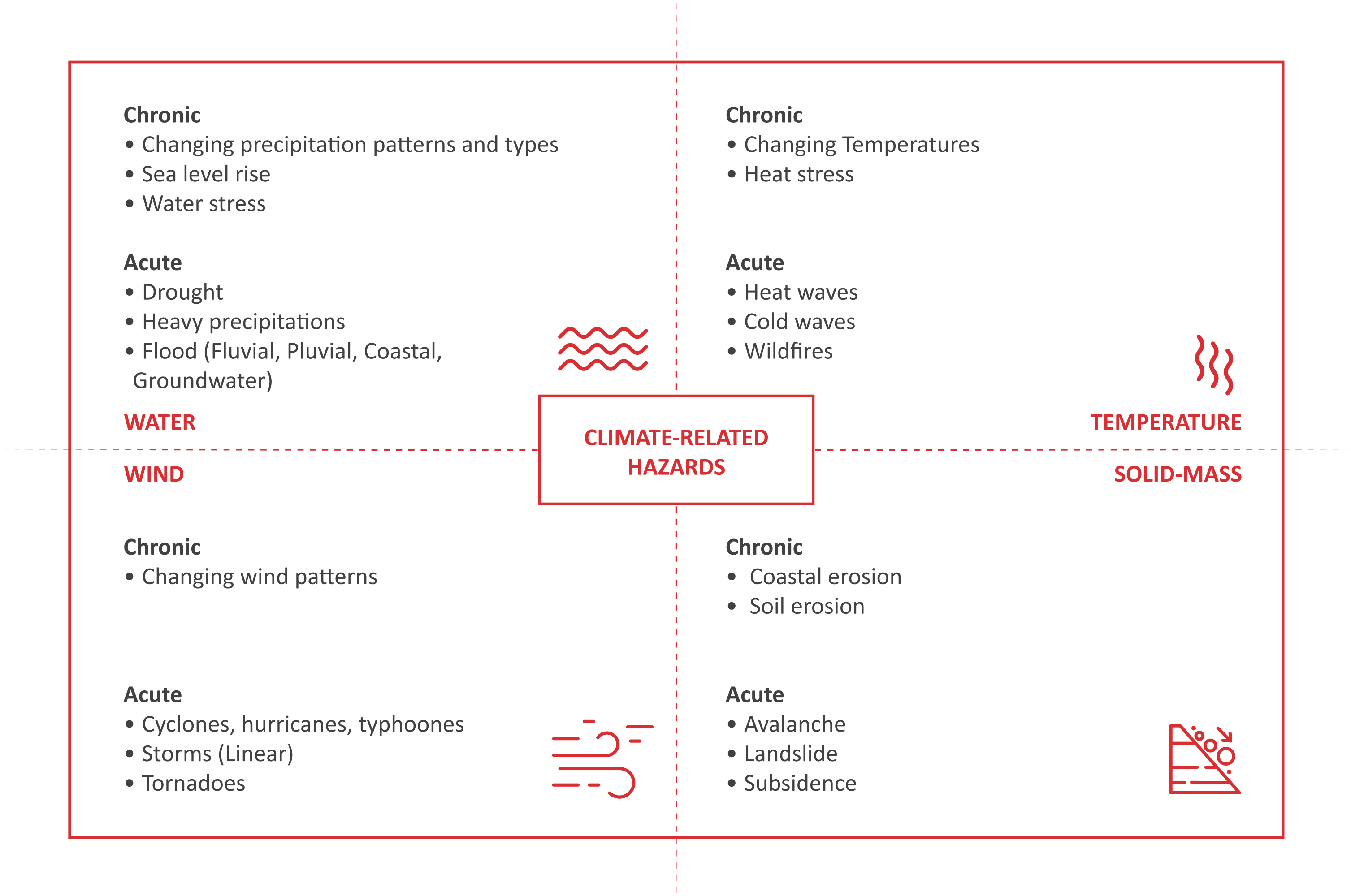
The future...

IPCC underlines that reducing emissions is key to limit changes, but continued emissions will trigger larger, faster shifts across regions. It is crucial that emissions are reduced drastically and rapidly. But we also need to accelerate adaptation of existing buildings and design future buildings to deal with the unavoidable climate effects already set in motion.



Sea level may continue rising throughout this century and for millennia thereafter. For a warming of around 1.5 °C, long-term global mean sea level could eventually reach a couple of metres over about 2,000 years. While these are indicative with substantial uncertainty, coastal adaptation will be crucial. (Image: Arup (2026); based on data from IPCC AR6 WGI (2021)).

Climate impact and buildings:
Insights on why buildings need to adapt fast



Hazards according to the EU Taxonomy, Objective 2, Climate Adaptation; Annex I, Appendix A.

This (non-exhaustive) table identifies climate and weather-related hazards that need to be studied under the EU Taxonomy Objective 2 (Climate Change Adaptation). Those in this table are recurring hazards typically deemed materials when developing EU Taxonomy-aligned reporting.

This regulation, at least in Europe, has driven in the last years a more thorough consideration of climate hazards on economic activities concerning new buildings and retrofitting or expansion of existing buildings, not only for those required to comply, but more in general. It is expected that certifications such as LEED Version 5 will also continue to increase emphasis on climate adaptation and resilience for buildings.

(Image: Arup, 2025; based on EU Taxonomy Annex I. Appendix A from European Commission (2021)).

Climate impact and buildings:
Insights on why buildings need to adapt fast

Buildings are both vulnerable to climate-related acute shocks and chronic stresses. They also contribute to localised climate impacts – particularly through the urban heat island effect in high-density areas.

Adapting both new and existing building stock to a changing climate is a pressing societal challenge, because of the unprecedented dual challenge of climate change destructive forces and transformational pressures.

Over 7,000 major recorded disaster events between 2000-2019 manifest the scale of the problem. This resulted in loss of lives and almost US$3 trillion in global economic losses. This data also show an increase from the previous two decades (1980-1999), when approximately 4,000 events caused over US$1.5 trillion in damages. Most significantly, climate-related disasters alone rose from 3,656 events (1980-1999) to 6,681 events (2000-2019), with floods more than doubling and storms growing in occurrence.

Though data disaggregated for buildings is not widely available, it is plausible that the effect of these disasters on residential, commercial, public and productive building has been very significant. In addition to direct destruction, buildings also face transformational pressures from increasing cooling demands. Global energy demand from air conditioners is projected to triple by 2050 and electricity consumption for residential cooling could double by 2050. Other estimate consider that commercial buildings could see a 30% increase in cooling demand. While estimates and figures vary significantly, the trend for an increase in electricity for cooling is plausible.

In addition to being exposed to the negative effects of climate change, buildings are also significant contributors to the urban heat island (UHI) effect, where cities experience higher temperatures than surrounding rural areas, especially at night, where temperature difference can reach up to 10°C during heatwaves or other extreme events. In a context of climate change, with increasing average and extreme temperatures, the role of building design in warming cities is crucial, and cannot be ignored. Product properties, colours, massing, geometry, layout and density are all parameters that can be considered to mitigate the negative effects of buildings in cities in a warming climate. Dark, low-albedo surfaces absorb more solar radiation, and building products with high thermal mass store heat during the day releasing it at night, limiting cooling. Satellite analyses show that dense arrangement of tall buildings generate urban canyoning effects, with spatial parameters such as height, density, and surface materials driving localized temperature increases, especially at the land surface.

>> Building must simultaneously mitigate climate-induced hazards, urban heat island effects, and energy demand escalation through integrated strategies across building and urban scales. This is an unprecedented challenge that will define the design practice now and in the foreseeable future.

Extreme Flooding
Valencia, Spain

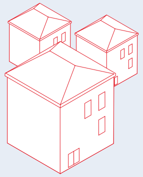
In October 2024, eastern Spain was struck by a catastrophic weather event caused by a DANA (Depresión Aislada en Niveles Altos, or isolated high-level depression). In Turís (Valencia), ~772 mm of rain fell within 24 hours, including a record-breaking ~184 mm in a single hour—the highest hourly rainfall ever recorded in Spain in low-lying urban areas of l'Horta Sud, floodwaters reached depths of up to 3 meters contributing to widespread devastation and a death toll of 232 people.

Hurricane Helene
Florida, United States

In September 2024 Hurricane Helene impacted Florida's Big Bend region as a Category 4 hurricane, producing severe inland flooding, extreme winds, storm surge, and multiple tornadoes across the southeastern U.S.
Resulting in minimum 250 fatalities, it is the deadliest hurricane to impact the contiguous U.S. since Katrina in 2005. Over 31,000 buildings were affected, with an estimated $12.5 billion in property value threatened across the most severely impacted areas.

Severe Heatwave
New Dehli, India

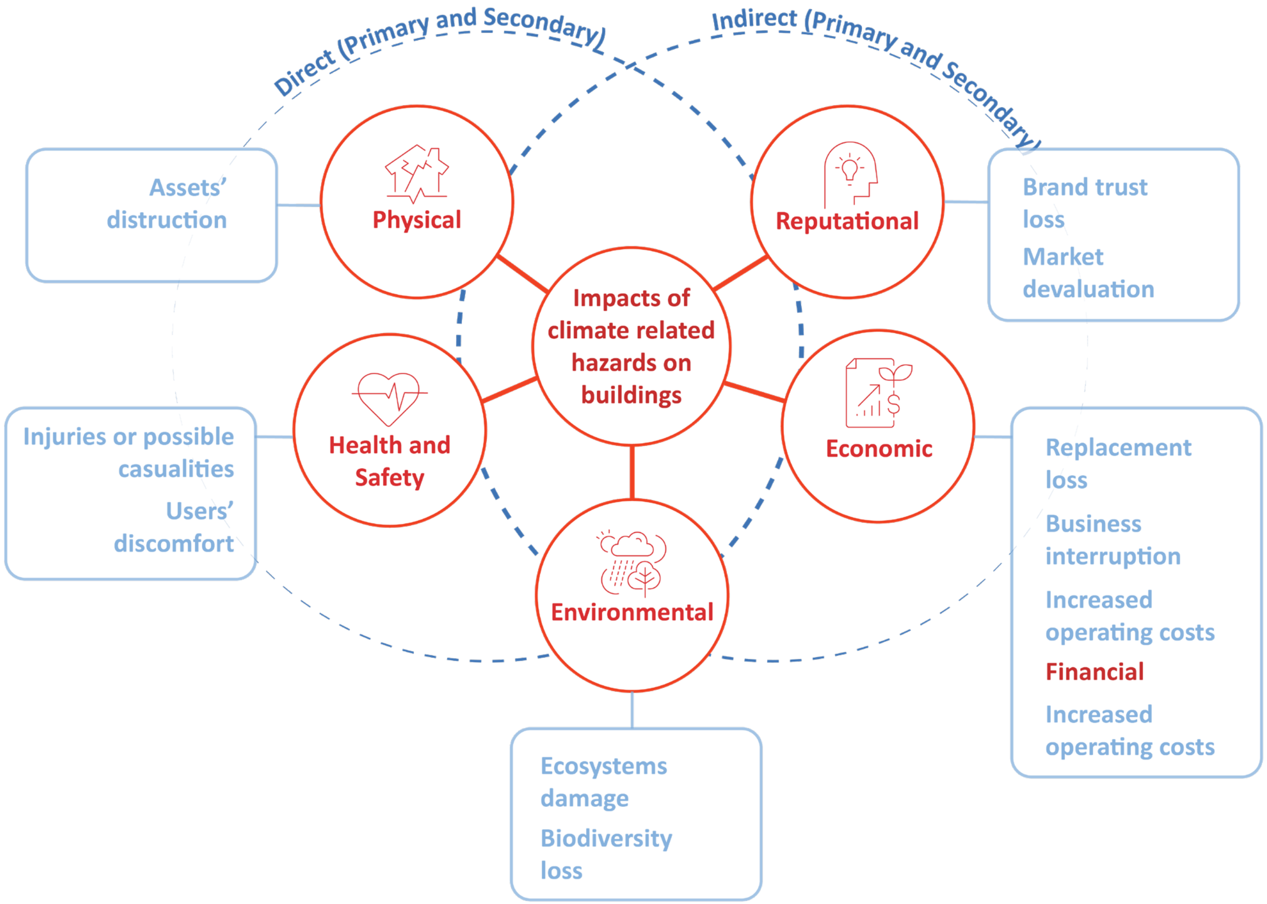
The India Meteorological Department (IMD) recorded 77 heatwave days in the country during summer 2024. Studies have shown that UHI intensity over various Indian cities tends to peak at night, ranging from 2.0 to 10.3 °C. Strong evidence links increased mortality to heatwaves. In 2024, the National Heat-Related Illness and Death Surveillance (NHRIDS) system recorded 48,156 suspected heatstroke cases, 269 suspected heatstroke deaths, and 161 confirmed heatstroke deaths. Heat in the built environment is more than ever a health emergency.



Examples in 2024 have clearly highlighted the vulnerability of the built environment.

1. Sedavì, Valencia, Spain - Flood
2. New Orleans, Louisiana, US - Hurricane
3. New Dehli, India - Heatwaves

Climate impact and buildings:
Insights on why buildings need to adapt fast



The impact of climate change on buildings extend beyond physical impact or energy demand.
From the integrity of the asset itself to broader and ramified societal and economic consequence chain of climate change on buildings. Owners, managers, tenants and insurers need to understand this impact chain to align their priorities. (Image: Arup, 2025).

Key Drivers for Climate Adaptation in Buildings

Three main drivers are leading the climate adaptation agenda in the building sector.

Environmental hazard profiles may be exacerbated by climate change effects. The risk of assets being affected by natural hazards may grow with increasing temperature, enhancing the probability of destructive impact and operational impairment that different stakeholders in the construction solutions' sector have an interest in preventing or mitigating, ranging from investors and developers to asset managers, as well as tenants and the local regulators. This increasing awareness is driving many actors to take steps to understand risk and devise adaptation measures for existing buildings; and developers, designers and regulators to find ways to integrate climate uncertainty into new designs.

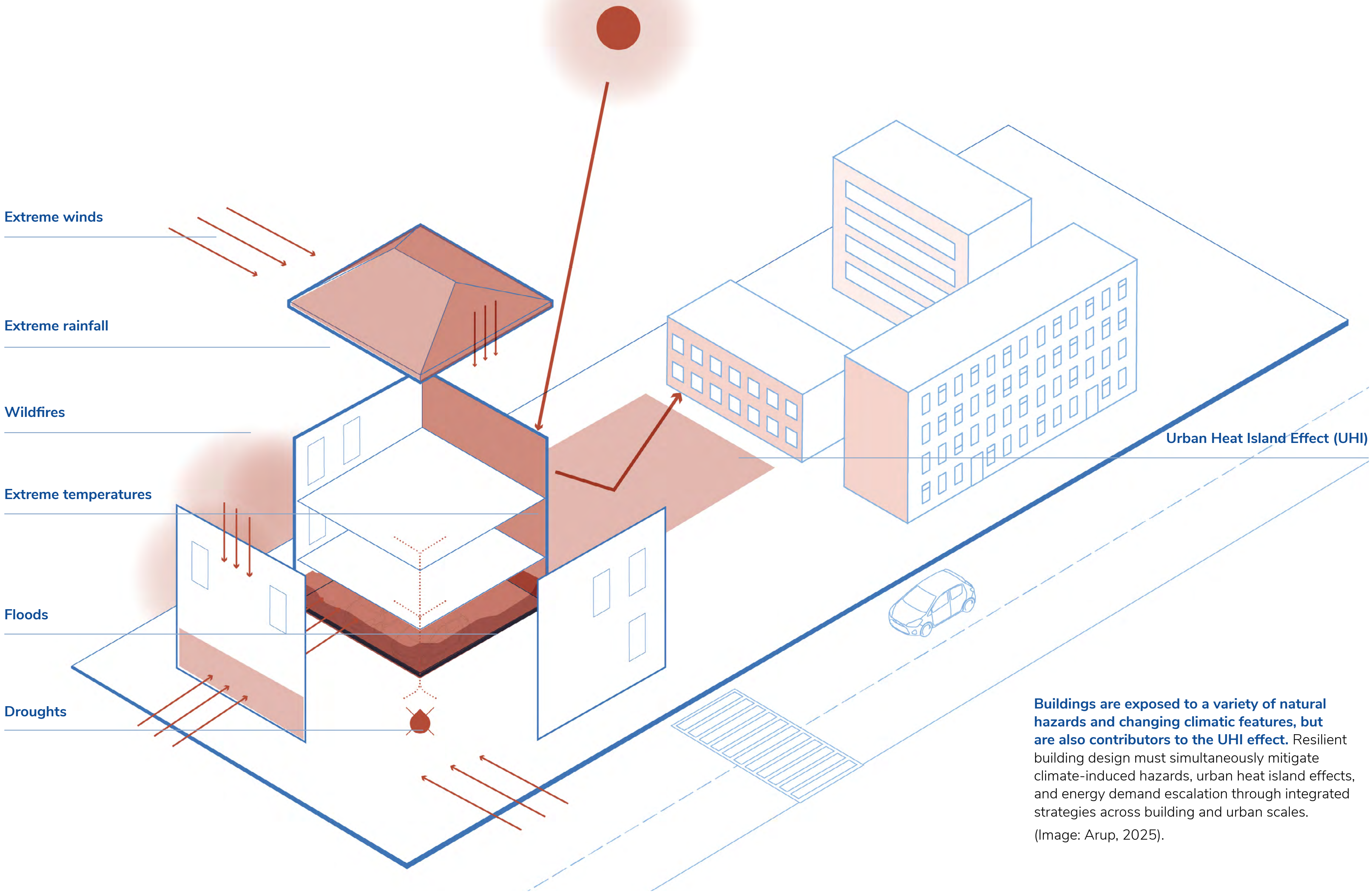
Norms, globally and nationally, and finance-linked regulation are accelerating after a slow response to climate risks – in particular due to costs and time needed to alter and update codes. The World Bank's 2025 Global Assessment of Building Codes confirms that most countries have traditionally relied on historical climate data rather than forward-looking projections, with codes typically updated in reactive multi-year cycles that have proven to be inadequate for current climate conditions.

A transformation is happening though with the International Code Council's 2024 I-Codes incorporating enhanced flood resilience, simplified wind zones, and wildfire safety measures specifically designed for climate hazards. Canada's National Building Code completed substantive climate integration through a $42.5 million research program, with implementation finalized in 2025.

The UK Climate Resilience Roadmap launched in July 2025 demonstrates this shift, with over 60% of climate hazards now receiving the highest urgency scores - a staggering increase that has catalysed immediate regulatory action. The EU's Corporate Sustainability Reporting Directive (CSRD), mandatory since 2025, requires climate adaptation disclosures, now with the EU Taxonomy's Climate Adaptation Objective 2 driving players in the building sector to systematically consider climate impacts.

Financial drive is also increasingly influencing the adaptation agenda. Data differ across regions, but asset under management (AUM) in the real estate at-risk from hazards such as floods and winds amount to several trillions of US$. Climate impact may bring portfolio devaluations, affect property valuations and insurance costs.

Jones Lang LaSalle (JLL) estimates that approximately $580 billion (37%) of European commercial real estate stands in the top 10 most climate-vulnerable cities. Recent data shows insurance costs are now the fastest-growing expense for building owners, with US commercial premiums increasing 88% over five years. Climate adaptation investments could generate $7.1 trillion in net benefits by 2030, while recent studies show that neglecting physical risks can lead to as much as 82% underestimations of Value-at-Risk for investors. JLL also estimates that owners will spend more on climate resilience by 2030, and that investors will likely favour buildings that are resilient to climate events. These drivers are leading more and more actors to conduct asset or portfolio-wide Climate Risk Assessment, from qualitative to quantitative studies, to understand the risk and Climate Adaptation plans to devise adaptation on existing assets and to find new ways to integrate climate change in new design. The following chapter reviews the practice through which this is being currently done.



Buildings are exposed to a variety of natural hazards and changing climatic features, but are also contributors to the UHI effect. Resilient building design must simultaneously mitigate climate-induced hazards, urban heat island effects, and energy demand escalation through integrated strategies across building and urban scales.

(Image: Arup, 2025).

Designing for uncertainty: Insights into the practice

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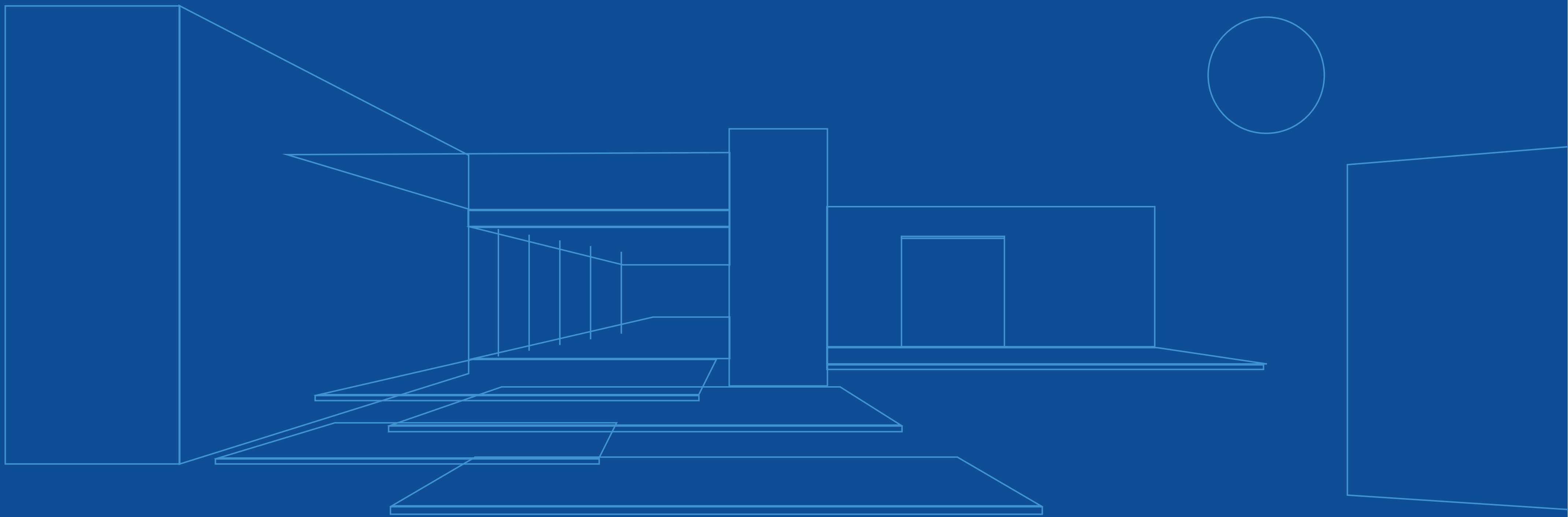
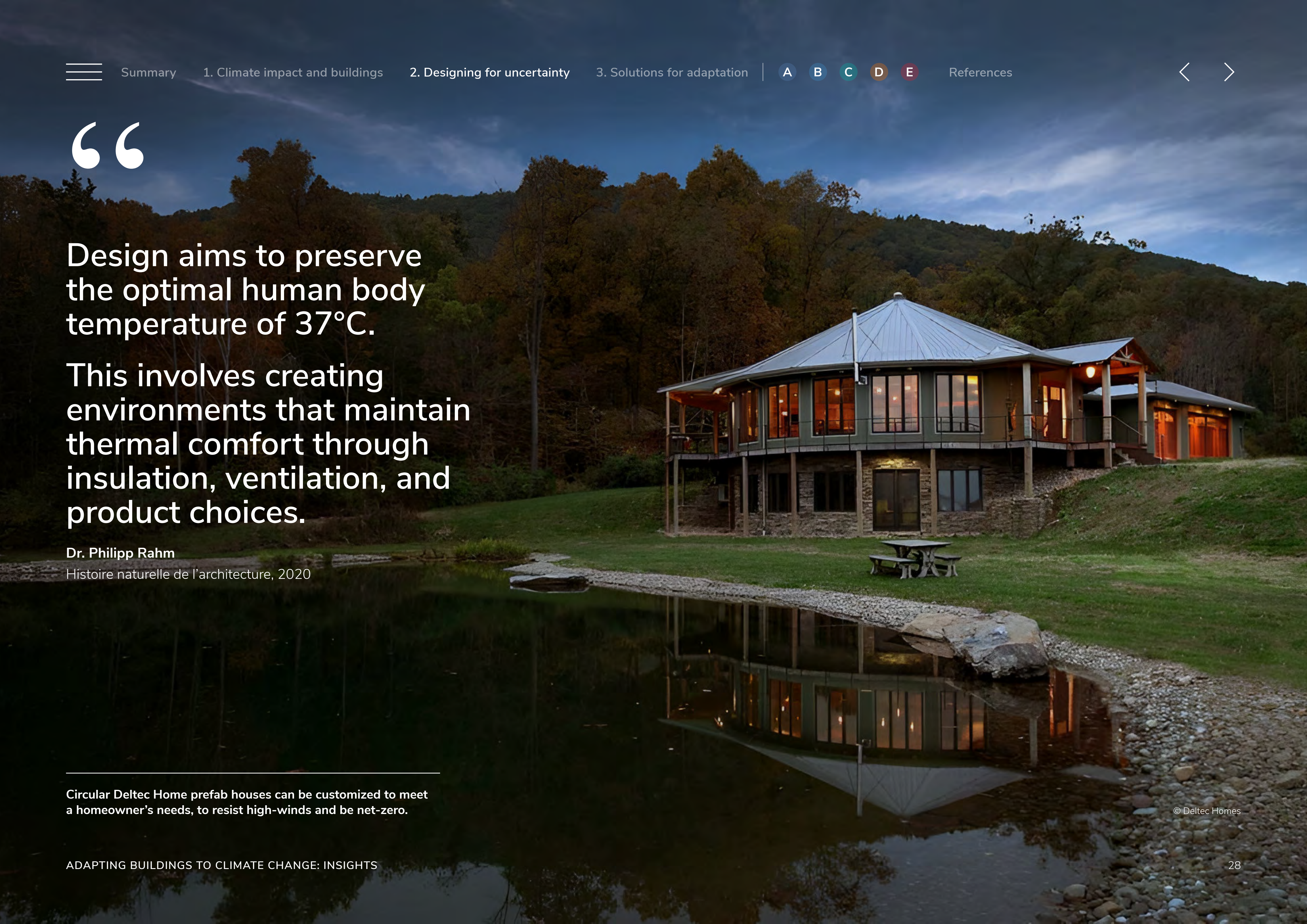




“

Design aims to preserve the optimal human body temperature of 37°C.

This involves creating environments that maintain thermal comfort through insulation, ventilation, and product choices.

Dr. Philipp Rahm
Histoire naturelle de l'architecture, 2020

Circular Deltec Home prefab houses can be customized to meet a homeowner's needs, to resist high-winds and be net-zero.

Designing for uncertainty:
Insights into the practice

Buildings are directly affected by present and future climate impacts, and may contribute to climate risks in built-up areas: In this chapter, we present ways in which the practice is integrating uncertain climate futures into the design workflows.

- Design is a balancing act – In the decades to come, adaptation will become a central driver in this process
- Retrofitting existing buildings requires at-scale, combined action
- Resilience can be achieved through an intelligent mix of robustness, adaptiveness and flexibility
- Current adaptive design practice includes several entry-points, from risk analytics to digital
- Performance and prescription need to be complementary to enable deep transformation in the practice


© Jake Waffles I Unsplash

Designing for uncertainty:
Insights into the practice

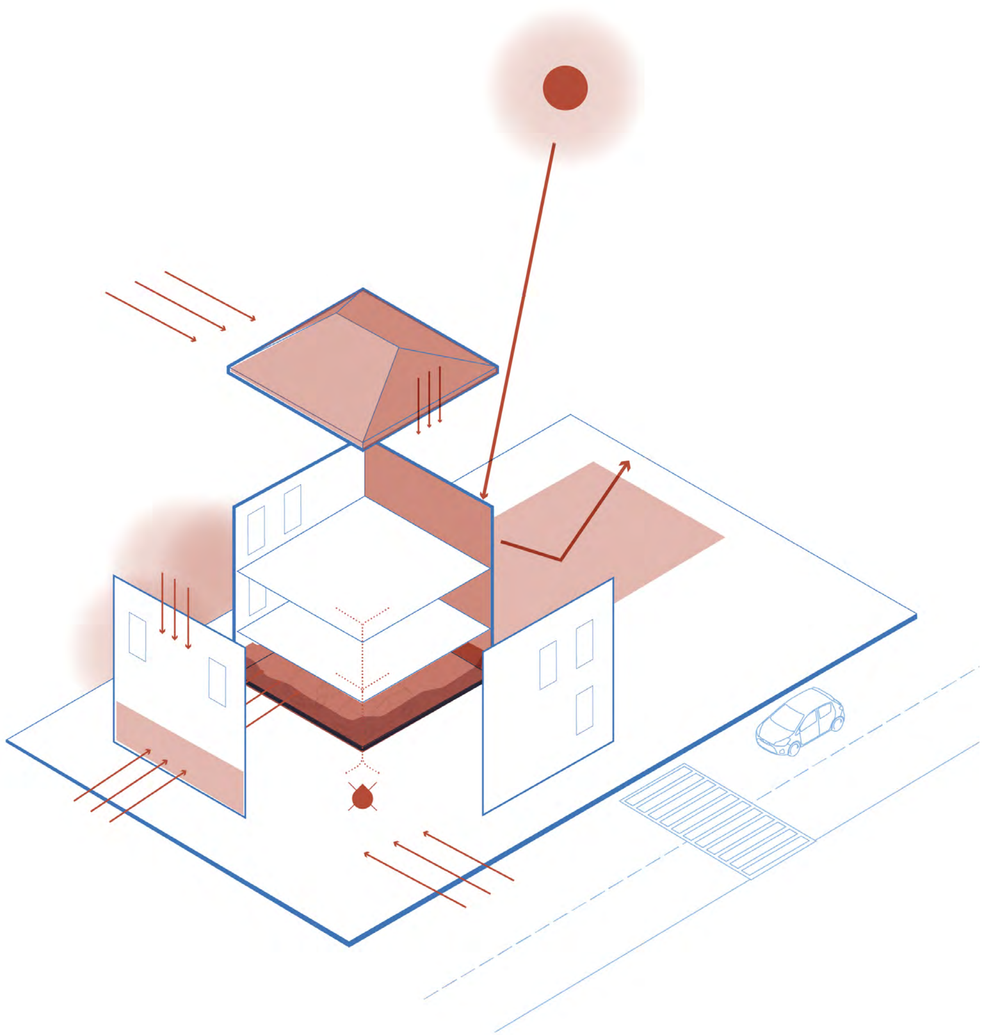
Building design is inherently a balancing act: climate change places new emphasis on adaptation, to be achieved alongside traditional comfort, aesthetics and overall performance and sustainability criteria.

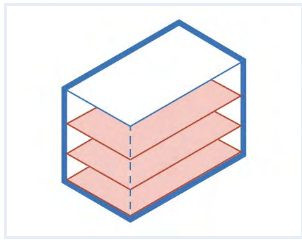
Quality design results from balancing values such as comfort, safety, cultural significance, durability, affordability and sustainability. The ability to further embed climate responsiveness into this balance is likely to become a defining technical and professional focus of the coming decades.

Practically, this involves pursuing long-term climate adaptability without reducing buildings to defensive bunker-like typologies. In essence, this means adopting resilience-based mixed strategies rather than focusing solely on calculating higher climate loads, and recognize that design, albeit critical, is only one step of a longer journey across all stages of a building lifecycle - from planning to long-term operation & maintenance. A key dimension of this integration is aligning mitigation and adaptation objectives. Over the past decade, the building value chain has made tremendous progress in reducing embodied and operational carbon. As climate impacts intensify, resilience must now be treated as a co-equal criterion alongside carbon throughout the planning, design, and materials' or construction systems' selection process.

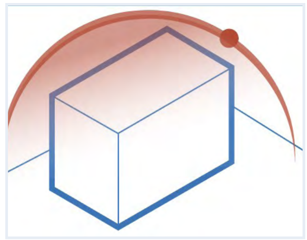
Tensions between carbon efficiency and hazard resilience are often perceived, as lightweight, material-efficient solutions may conflict with the durability required to withstand increasing climate stresses. These tensions are not absolute: careful selection of materials, products, and systems can reconcile carbon and resilience objectives. For example, materials with slightly higher embodied carbon but superior durability can extend service life, reduce replacement cycles, and lower whole-life carbon, while maintaining operational performance under climate extremes. Innovations in resilient products, integrated systems, and adaptive construction techniques further expand these opportunities. Material and system selection is therefore central to balancing performance, resilience, and carbon outcomes, but it must occur within the broader design process, accounting for building function, context, and lifecycle interactions. Effective climate-responsive design requires evaluating solutions across durability, operational performance, embodied carbon, and hazard resilience, optimising outcomes over the full building lifecycle and across scales—from individual products to systems and the urban context.

>> In the next decades adaptation should become a central driver of design - a key parameters alongside carbon efficiency, comfort and attractiveness. A quality building will be a sustainable and resilient one.

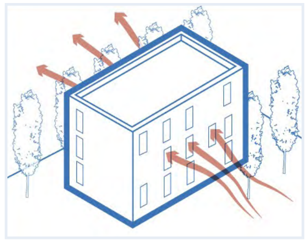




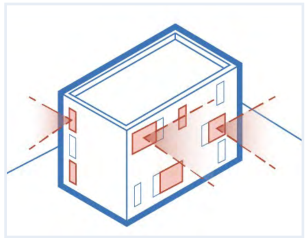
GFA



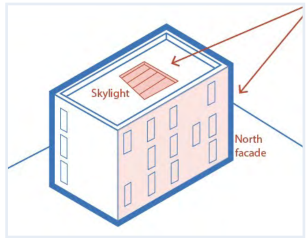
Sunlight



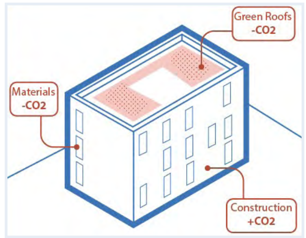
Wind



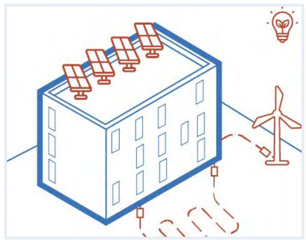
Views



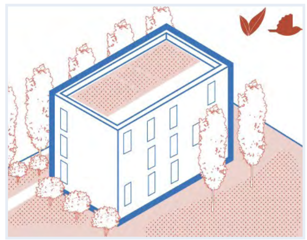
Daylight



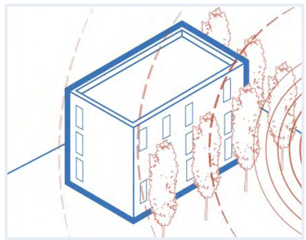
Carbon



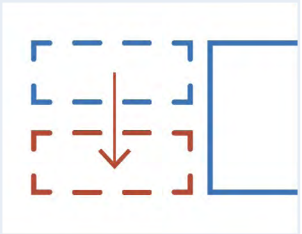
Energy

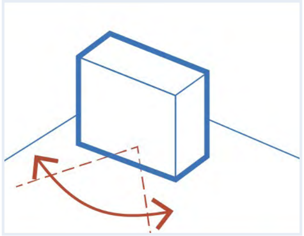


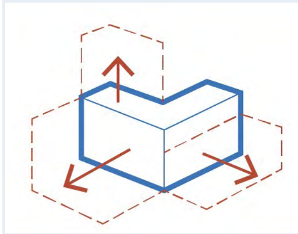
Biodiversity

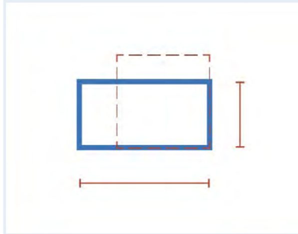


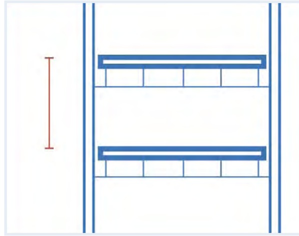
Noise

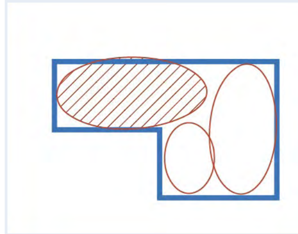

Siting

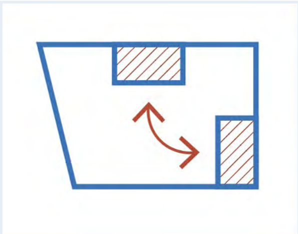

Orientation

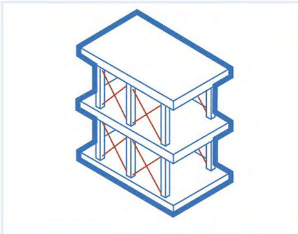

Shape

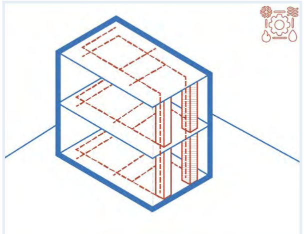

Floorplate

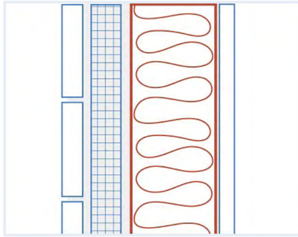

Flr to Flr height

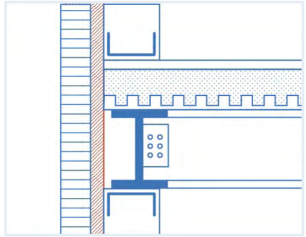

Interior layout

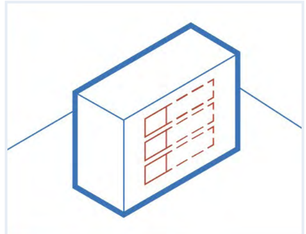

Core location

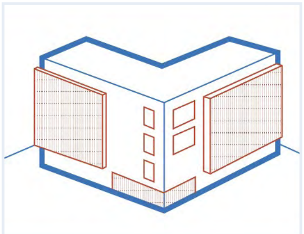

Structure

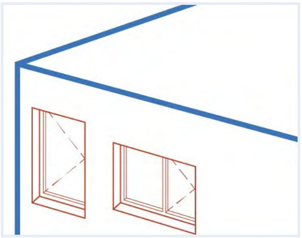

HVAC systems & BMS

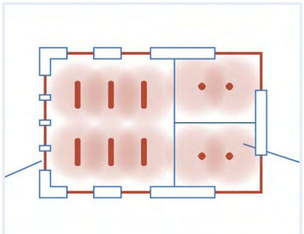

Insulation

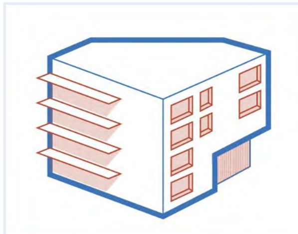

Thermal bridge

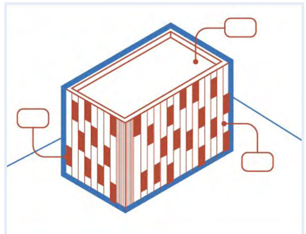

Glazing ratios

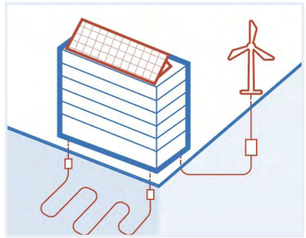

Glazing location


Glazing shape


Lighting


Solar protection


Exterior products


Renewables

Design entails optimising multiple, often interdependent (sometimes conflicting) requirements, constraints, and performance parameters to achieve targeted outcomes. Resilience constitutes a key design objective, emerging from the integrated coordination of these parameters across systems and scales.

(Image: Arup 2026; based on multiple sketches).

Designing for uncertainty:
Insights into the practice

It is estimated that the 80% of the buildings standing in 2050 already exist today in advanced markets, and a smaller percentage in developing markets. Achieving climate-responsive communities and cities will therefore require significant retrofitting, risk management and risk transfer efforts.

Retrofitting existing buildings—often designed using standards that no longer reflect rapidly changing climate—is a challenge of scale, with significant implications for how cities and societies withstand future climate impacts.

Annual new construction represents only a small fraction of the existing building stock in advanced markets, making renovation essential. An estimated 80% of buildings standing in 2050 already exist today, in advanced economies. For example, the United States has over 100 million buildings, with only about 1% of the total built new each year, most being single-family homes. In fast-growing economies—such as India or countries in Southeast Asia and Africa—a significantly smaller proportion of today's buildings is expected to persist to 2050. Given the high vulnerability of both the stock and communities that depend on it, prioritizing retrofitting to adapt to climate change remains crucial at a global level.

Retrofitting can appear costly, with procurement hurdles and limited regulatory incentives—yet technical solutions are widely available and feasible. In addition, energy-efficiency initiatives, such as the EU's Renovation Wave, demonstrate that scaling up solutions is possible, offering major opportunities for mitigation and adaptation.

Where feasible, adaptation strategies can be paired with tailored risk-transfer mechanisms; however, the stance on climate-related events is still evolving (often reflected in rising insurance premiums and restricted coverage), and varies greatly across regions.

Technical solutions exist, but meeting the challenge at scale will require collaboration among designers, regulators, investors, construction professionals, and insurers.

>> The scale of retrofitting is large but achievable with integrated, long-term strategies. Buildings can be upgraded at scale to withstand future climate hazards and deliver lasting value for communities.

80%
30%

Percentage of buildings existing today believed to still exist in 2050 in developed markets, including Europe and the US.

Average estimated percentage of buildings existing today expected to still exist in 2050 in emerging markets (Approximate estimates range 20%-40%, varying across geographies).

Designing for uncertainty:
Insights into the practice

Resilient buildings are achieved through a composite strategy ranging resistance-based thinking to future-ready adaptive and flexible design. This leverages both risk reduction by design—diminishing components' sensitivity and exposure to climate impacts—and enhanced capacity to function during and recover rapidly after adverse events without catastrophic failure or major disruption.

The combination of resistance, adaptability, and recoverability within a single system defines resilience in buildings. Three complementary approaches work to enable long-term performance under uncertain climate futures.

Robustness – The 'fortress' approach

This approach emphasizes resistance to damage using high-strength, redundant and durable systems.
It emphasises, for example, reinforced assemblies designed to withstand extreme flood, wind loads and heat waves, reflecting traditional hazard protection methods. Structural and envelope redundancy is implemented to ensure safe failure modes, preserving critical building functions even under stress. Climate simulation testing – such as high wind and rainfall pressure assessments – validates watertightness and structural performance under projected future conditions. Robustness is indispensable where failure is not an option due to regulatory, operational, or safety requirements but under climate uncertainty needs to be complemented with adaptive and flexible solutions.

Adaptiveness – The accommodation approach

This approach focuses on solutions that enable active interaction with climatic stresses and shocks, avoiding catastrophic failure while allowing controlled, non-critical impacts. Its priority is to maintain functionality and usability during and after an event, rather than pursuing absolute resistance or complete avoidance of damage. For example, wet flood-resilient designs permit managed water ingress without compromising structural integrity, significantly reducing recovery time and repair costs. By maximising a building's capacity to perform within its current and future environmental context, this approach supports long-term operational continuity. It also reduces sole reliance on oversizing and over-dimensioning—key considerations since designing for absolute worst-case climate scenarios is often technically challenging and economically prohibitive, which may pose an obstacle to adaptation for some actors in the value-chain. This approach aims at performance optimisation under uncertainty.

Flexibility – The dynamic approach

This approach prioritizes long-term flexibility, upgradeability alongside active monitoring of evolving climate scenarios. For example, Design for Manufacturing and Assembly (DfMA) and Design for Disassembly (DfD) enable replacement or upgrading of façade and structural panels with minimal disruption, should the need arise. Systems that maintain airtightness and watertightness under climate stress, while also facilitating retrofits in uncertain futures are favoured. Performance-based façade monitoring (such as thermography) may predict product degradation and schedule proactive maintenance. Lifecycle thinking ensures that buildings can evolve over time rather than merely endure as long as possible, acknowledging that not all events can be anticipated and designed for, especially as climate scenarios are uncertain.

>> Designers can integrate robustness, adaptiveness and flexibility in design processes.

Robustness

#resisting #protecting

Build robustness into the project, use stronger products, increase design loads and enhance specifications. Contrasting destructive forces with strength and redundancy.

Metal studs and steel to resist extreme loads with robustness and redundancy.

© FoxBlocks ICF

Precast concrete hurricane shelters to resist and protect.

© Wieser

Flood-gates work to protect by excluding and deflecting forces.

© Aggeres

Adaptiveness

#adapting #accommodating

Float along, make room for uncertain events, let basements flood: resilience may be achieved by accommodating natural phenomena instead of contrasting them.

Schoonship floating homes in Amsterdam are adapted to work with the river and its hydrodynamics.

© Schoonship Project, Isabel Nabuurs, Netherlands

Elevated housing in Mekong, Vietnam, are adapted to the prevalent environment, and accomodate recurring riverine inundation.

© Red Shuheart I Unsplash

Metropol Parasol timber shading system for public open spaces in Sevilla, Spain shelters from sun and induces airflows against heat.

Engineers: Arup. Architect: J. Mayer H. Architects © Arup

Flexibility

#flexing #replacing

Build flexibility and dynamism into the project using solutions that morph, allow for change, or even brake if necessary. Monitor, change and, ultimately, replace if needed, alongside an evolving climate. The inherent flexibility and resilience of ecosystems services are leveraged.

Raft foundation in the 50 Fenchurch St. building project allow for future redistribution of building loads and steel and precast frame allowing for partial dismantlement or extension without major structural modification.

50 Fenchurch Street, London, Building Design
© Paul Carstairs/Arup

The modular façade of the Al Bahr Towers, composed of replaceable units, is a kinetic shading geometry, mashrabiya-inspired system that dynamically moves in response to solar radiation through advanced Building Management System.

Engineers: Arup. Architects: Aedas
© Abu Dhabi Investment Council headquarters

“Living roof” of the California Academy of Sciences, San Francisco, covered with 1.7 million plants for thermal regulation, storm-water retention, biodiversity, and reduces building heat gain.

Engineers and sustainability: Arup. Architect: Renzo Piano Building Workshop (RPBW)
© Cody Andresen/Arup

The Case for Transferring Risk

Insurance is an effective and rapidly expanding field to transfer part of the risk for buildings.

"

Risk can never be fully eliminated — only reduced, mitigated, or managed.

Risks that persist beyond the design phase and must be addressed throughout a building's lifecycle with incremental measures such as retrofitting, performance monitoring, or tactical interventions (for example, deployable flood barriers or removable gates).

In some instances, however, residual risk—the portion that cannot be practically reduced through design or operation—can and should be transferred to financial mechanisms such as insurance or reinsurance. The insurance sector is increasingly integrating climate-related hazards into underwriting, asset valuation, and pricing models, reflecting the rising frequency, severity, and loss potential of extreme events.

While risk transfer mechanisms are mature in the US and parts of Europe, they are rapidly evolving in other markets as climate change reshapes exposure profiles and challenges the insurability of assets within the built environment.

For example, Fortified is a system promoted by an association of insurance companies, The International Institute for Business and Home Safety. It is a system of "above code" construction guidelines meant to increase the resilience of structures and reduce the premiums to insure those buildings. Some affected states, such as Alabama, recognize the impact of these improvements and offer incentives of as much as $10k to upgrade an existing home.

Special attention has been paid to elements that increase a buildings resistance to elevated wind speeds, larger quantities of wind driven rain, as well as impact from larger diameters of hail. As an indication of the growing risk to insurers, the IBHS recently launched a new program intended to specifically improve a home's resistance to wildfire. That program is called Wildfire Prepared.

In North America, flood is not covered by typical residential insurance policies and has special considerations. While coverage can be obtained through a small selection of specialty underwriters and the National Flood Insurance Program, the cost is much greater than typical coverage. If a covered property is damaged by flood, rebuilding to a higher standard of flood resistance is required; the American Society of Civil Engineers (ASCE), Flood Resistant Design and Construction, ASCE 24 is the standard. To help cover the costs of meeting their elevated requirements, the National Flood Insurance Program offers Increased Cost of Compliance (ICC) coverage grants of up to $30k per home.

Lucas J. Hamilton, Saint-Gobain

Designing for uncertainty:
Insights into the practice

There are at least six distinct methods through which resilience and adaptation are currently integrated in the design process. These methods may be applied at different stages, and by different disciplines, each with its opportunities, and challenges.

> Understanding risk, both now and in the future, is increasingly central to contemporary building design. Climate Risk Assessments (CRA) are evolving from qualitative to quantitative approaches, systematically integrating hazard-specific and multi-hazard data under dynamic future climate scenarios.

These assessments have shifted from reactive to proactive tools, evaluating current and future climate conditions using advanced modelling frameworks. International standards, particularly ISO 14090 and ISO 14091, provide systematic guidance for climate risk assessment and adaptation planning. Traditional risk equations (R = H × E × V) remain foundational, combining hazard, exposure, and vulnerability, and are now augmented with temporal projections from CMIP6 climate models, offering enhanced spatial resolution and ensemble analysis. Common practice compares scenarios such as SSP2-RCP4.5 and SSP5-RCP8.5 across the lifespan of existing and new buildings, considering direct changes in temperature and rainfall alongside evolving hazard profiles. Spatial resolution balances computational feasibility with analytical precision, with higher-resolution statistical downscaling recommended but often constrained by data availability. Risks are quantified using proxies such as Annual Average Loss (AAL) in US$ and downtime, which provide a measurable, objectified basis to evaluate cost-benefits of adaptation and retrofit measures for building designers, investors, owners and managers. This is valuable not only for single assets, but also for portfolios of assets.

While CRA methodology has advanced, uncertainties in long-term projections remain. Non-linear hazard attribution and scenario variability—particularly post-2050—require interpretation and synthesis capacities and sometimes assessments remain temporally static limiting direct application over evolving building lifecycles.

>> Expanding regulatory requirements, market incentives, and improved modelling tools are likely to broaden the application of CRAs as a starting point for design of new buildings, and retrofit of existing ones.

Designing for uncertainty:
Insights into the practice

> Architecture is the first port of call for adapting buildings, addressing climate pressures early and from the ground up. Building forms and techniques originally responded to environmental conditions to provide shelter and comfort and are now being called to re-center around climate responsiveness after a period prioritizing societal and cultural considerations. In the context of changing temperatures, extreme hazards, and long-term uncertainty, architecture is re-establishing resilience as a core design principle rather than an add-on applied after form, program, and aesthetics are defined.

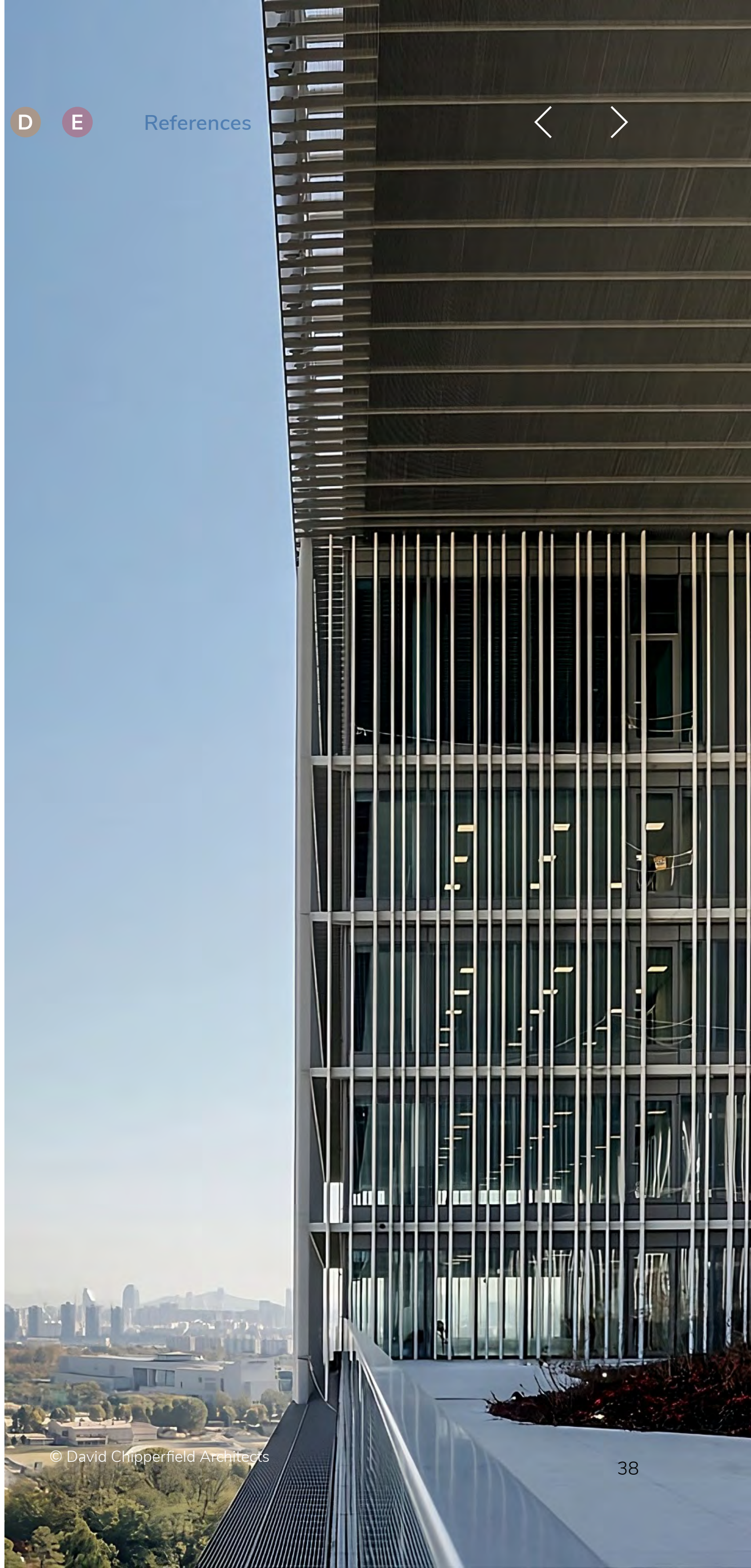
Contemporary practice interrogates building geometries, volumes, and spatial arrangements against current and projected climate conditions. Massing and orientation optimize passive ventilation, daylight, and thermal regulation, minimizing exposure to both current and future extremes. Volumes are articulated to reduce wind loads, manage solar gains, promote stack-effect cooling, and buffer exterior hazards, using spatial composition as an adaptive device. Site planning begins with mapping environmental threats: projecting flood lines, measuring solar access, analyzing topography for water retention, and hypothesizing building performance under varied scenarios—actions beyond regulatory standards. Façades function are conceived as dynamic interfaces, with layered assemblies, adjustable openings, and integrated solar protection to modulate indoor conditions. Permeability, durability, synergy with building form and thermal performance among others parameters influence architectural choices of construction systems early.

Adaptive strategies extend to landscape integration, where planted buffers, green roofs, and tree clusters form thermal barriers, manage runoff, and improve microclimate. This practice increasingly involves testing spatial and volumetric hypotheses using climate data and performance modelling for different futures, typically addressing adaptation before technical systems.

Yet the practice remains uneven. Coordination across specialists, reconciling resilience with programmatic and aesthetic priorities, and evaluating trade-offs in materials and form continue to be challenges.

Ultimately, the practice is often forced to recognise that single long-term fixed solution is not viable; buildings must function across a spectrum of plausible futures, allowing flexibility in spatial and volumetric responses. In some cases, this may mean accepting periodic flooding while ensuring buildings continue to operate without catastrophic loss.

>> By rethinking spatial arrangements, envelopes, geometries, site and environment relationships, architects have a major, fundamental, role in advancing climate adaptation and resilience.



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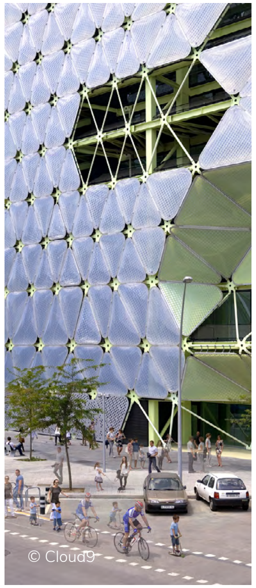
Designing for uncertainty: Insights into the practice

> Calculating design loads under uncertain climate scenarios is an evolving field*.

The engineering practice, within the broader building design practice, is moving beyond static, historically based codes toward forward-looking design strategies that anticipate future climate loads. While current standards like ASCE 7 or EN 1991 provide robust frameworks for historical conditions, they do not account for the accelerating frequency and intensity of extreme weather events. As a result, architecture, engineering, and construction professionals are increasingly relying on dynamic models, modified climate scenario data, and integrative resilience measures to future-proof buildings.

A central shift in climate adaptive design lies in the treatment of structural loads. For instance, on wind loads a number of existing codes still rely on stationary extreme value statistics and primarily capture synoptic-scale events, but many future risks — such as convective downbursts — fall outside these bounds. Advanced engineering standards now emphasize non-stationary design approaches informed by global climate models (e.g., CMIP6) and regional downscaling.

Parallel advancements are taking place in envelope and façade design, especially in response to rising ambient temperatures and heatwaves. Practice here increasingly leverages future-shifted weather datasets (e.g., RCP8.5) to guide product selection and thermal strategy. Indicatively, exterior wall assemblies are now designed to achieve lower U-values through continuous high-performance insulation, paired with ≥200 mm of thermal mass targeting a time lag of over six-eight hours. These assemblies integrate vapor-open membranes (sd ≤ 0.2 m), airtightness of ≤0.6 ACH at 50 Pa, and spectrally selective glazing with double or triple glass unit according to climate zone, with balanced window-to-wall ratio. Roof assemblies follow suit, being highly insulated and with highly reflectance finishing (SRI ≥ 80) and ventilated cavities to reduce thermal ingress and enable survivability during outages. Passive design principles are further supplemented by dynamic solar protection and reflective architectural skins that minimize both cooling loads and external urban heat island effects. These envelope solutions are validated through dynamic energy modelling (e.g., EnergyPlus) and hygrothermal simulations (e.g., WUFI), particularly to assess condensation risks under high humidity and varied dew point profiles.


© Cloud9

Media-ICT building CZFB

In the Innovation District of Barcelona this building couples the use of smart products -specifically the ETFE system-, and an optimised design tailored to the building's façade orientations make the exterior of this structure one of its most distinctive architectural features. On one side, the main façade is clad with cushion-like elements made from a transparent, non-stick plastic (ETFE) that can inflate or deflate in response to data gathered by flow meters monitoring sunlight exposure. When inflated, these cushions function as diaphragms to block direct sunlight. On the southwest façade, a different strategy is employed: fine particles of liquid nitrogen are misted between ETFE layers, allowing the façade to dynamically adjust its opacity in response to varying light conditions.

One Tower after Hurricane Laura

Tall buildings, due to their height and complexity, might be vulnerable to wind loads, which can cause structural damage and significant economic losses, both direct and indirect, such as business or transportation disruptions caused by debris from falling façades during high-intensity winds. Common types of damage include broken façades, windows, and structural connections, caused by airborne debris or wind pressures that exceed the specified design thresholds. A notable case is the Capital One Tower in Lake Charles, Louisiana, which, after suffering damage from several hurricanes between 2005 and 2020 ultimately leading to demolition. These events highlight the need to improve design and assessment standards to ensure the safety and resilience of tall buildings.


© Joshua Pugh

*The values presented are indicative, based on temperate-climate best practice; actual targets depend on climate zone, building type and codes. They should not be considered as guidance and instead different applicable standards should be taken into account.

Designing for uncertainty:
Insights into the practice

HVAC design loads are also increasingly influenced by considerations of future climate conditions. System sizing now incorporates peak loads derived from changing climate data, accounting for rising dry/wet bulb temperatures and latent humidity. To maintain flexibility and energy efficiency, many HVAC systems now integrate inverter-driven compressors, variable refrigerant flow, and low-GWP refrigerants (e.g., R-454B, R290), offering responsive load modulation. Cooling strategies such as indirect/direct evaporative pre-cooling and thermally activated chillers are selectively deployed in hot, arid climates, while free cooling systems are more often implemented in cold climates. Predictive building management systems (BMS), powered by AI and real-time weather data, enable optimized start-up sequencing, demand-controlled ventilation, and pre-cooling strategies. But calculating climate loads for distant, uncertain futures is not the only adaptive strategy. Anticipating future needs—for instance, by designing larger technical spaces that can accommodate future equipment—is often preferable to overspecifying machines. Where equipment lifespans are shorter than climate scenario timeframes—for example, a system installed in 2025 with a 15-year lifespan requiring replacement before the 2050 climate horizon—spatial flexibility becomes the solution of choice. This strategy provides capacity for additional thermal generators, expanded storage systems, and backup power as conditions evolve.

Water management and drainage infrastructure design show similar shifts toward adaptive, climate-resilient approaches. System designs now use non-stationary rainfall intensities (derived from CMIP6-driven IDF curves) and hydrologic models that support compound event simulation, including high groundwater levels. Hydraulic modelling tools like SWMM, PCSWMM, or HEC-HMS support dual-drainage analysis identify bottlenecks and flooding risks. Adaptive components such as real-time controlled detention basins, anti-surcharge valves, and modular green infrastructure also add layers of redundancy and performance flexibility. This approach strive to accommodate projected increases in rainfall intensity, often on the order of 10–40% in many mid-to late-century scenarios and depending on the context, extending beyond traditional 1-in-100-year storm design assumptions.

>> Shifting data to different climate scenarios is critical to calculate loads. As climate models improve, codes evolve and the practice evolves these approaches are likely to progress and inform adaptive design.

The south-west stretch of the ring road - Moti bagh area of Delhi

Well designed Sustainable Urban Drainage Systems (SUDS) are an innovative and effective response to complement and support traditional urban drainage systems in the face of the growing challenge of flooding. Their main objective is to manage rainwater in a way that mimics the natural water cycle, incorporating solutions that retain, filter, infiltrate, store, and reuse stormwater within the urban environment itself, rather than rapidly discharging it through conventional drainage systems. The case of the New Delhi ring road represents a significant example of bioswales implementation for stormwater management, effectively mitigating stormwater and reducing flooding.

Designing for uncertainty:
Insights into the practice

> Managing residual risk and retrofitting is often a necessity: Once design is finalized, structural systems are calculated, or a building already exists, residual climate risks may persist that cannot be fully eliminated. These remaining risks must be reduced and managed through targeted interventions that preserve overall asset performance. Existing buildings, conceived under different climatic conditions, also require retrofit, often within limited possibilities.

Retrofitting or risk-reduction measures further reduce vulnerability or enable buildings to cope with adverse events. Legacy weaknesses may be addressed without compromising core functions, or risk further reduced without major alterations. Where major refurbishment is impractical, deployable resilience measures provide flexible mitigation: modular flood barriers—such as removable steel gates sized for 0.5–1.0 m water head—cyclone shutters rated for high winds, and inflatable flood tubes for rapid urban deployment. Blue-green retrofits attenuate stormwater and enhance biodiversity with minimal structural impact. Hybrid roofs combining intensive green systems (e.g. 80–150 kg/m² substrate) and blue storage layers retain in the order of 20–40 mm per event, depending on design and rainfall pattern, while permeable paving can reduce runoff peaks significantly, easing drainage networks.

MEP adaptations protect critical infrastructure by elevating switchgear, boilers, and HVAC condensers above the 100-year flood level plus 0.5 m freeboard or enclosing them in IP66-rated housings. Water-tolerant cabling and pump systems preserve post-event functionality. Passive strategies — including external louvres, operable vents, and thermal inertia products — reduce overheating where selective glazing is not feasible. Reflective façade coatings and phase-change paints further limit solar heat gain.

Implementation must navigate technical, regulatory, and operational constraints. Heritage protections may restrict external barriers, dense urban contexts limit green infrastructure coverage, and retrofit costs must be weighed against long-term benefits. Probabilistic multi-hazard scenarios (simultaneous heat, flood, and wind) exceed most model precision, but scenario-based frameworks support informed, performance-oriented decisions.

Working on residual risk is therefore practical either during the building lifecycle for existing stocks or where full climate-model-based adaptation is deemed uneconomical, although it should be noted that for new design this is no substitution for more fundamental architectural and engineering upstream adaptation and, for existing stocks downstream solutions may not always effective to the desired level.

Flood gate risk reduction solution © Lakeside Flood Solutions Ltd

> Construction technologies and systems provide a rich sandbox for designers addressing the adverse effects of climate change. By balancing adaptation, durability, cost, and performance, designers can evaluate integrated assemblies—combinations of materials, products, and technologies—that contribute to multi-hazard resilience across building components from structure to façade.

Many effective approaches to use specific construction systems have long-standing precedents, which innovation keeps on enhancing. For example, for flooding and heavy rains, permeable pavements, rain gardens, and bioswales reduce runoff, while green and blue roofs retaining water support vegetation and delay discharge. Previous concrete enhances infiltration at surface level, while waterproof membranes protect building structures from water penetration. To mitigate heat and solar gain, sequential strategies could be integrated within the building envelope: solar protection systems (solar-control glazing and shading devices such as overhangs and fins), heat-reflective surfaces ("cool" materials like reflective coatings and light-coloured cladding), and thermal envelope systems with insulation providing high thermal resistance, water repellency, and non-combustibility.

Under extreme winds, hurricane straps, steel clips, impact-resistant panels, storm shutters and safety glass protect the building envelope, while mesh screens prevent the ingress of debris or embers. Wildfire smoke and firebrands are countered with non-combustible cladding (metal, ceramic), airtight envelopes with high-efficiency filters, and sealed ventilation inlets. Integrated systems—such as inverted or ballasted roofs supporting PV or rainwater harvesting—and ventilated rainscreen façades further enhance resilience. This "taxonomy" of solutions is further explored in the next chapter. It is presented as a set of strategies that can be combined within a comprehensive architectural and engineering framework according to the context and design intent. These strategies could operate in two complementary ways: 1) sequentially—first blocking, then reducing, then accommodating—and 2) collaboratively, with components functioning together to enhance overall performance.

>> A wide range of construction technologies, systems, and products are available to support building adaptation, as further detailed in Chapter 3 of this document.

Designing for uncertainty: Insights into the practice

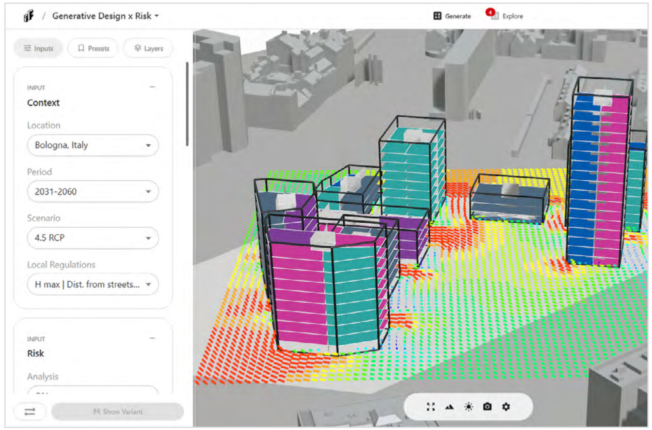
> Unlocking digital tools for climate adaptation: Practitioners are increasingly adopting computational, data-driven approaches to manage complexity and shifting conditions across multiple climate scenarios.

Early-stage site analysis now often incorporates climate projections and digital simulations to assess hazards, wind, and solar exposure. Parametric tools can rapidly generate and assess thousands of design options accounting for site data, client briefs, and regulations – and test building' behaviours in multiple climate scenarios. Each scenario is scored against performance metrics—comfort, energy, carbon, cost, and safety—enabling multidisciplinary collaboration and on-the-fly parameter adjustment, so teams can visualize trade-offs and optimize solutions. By quantifying apparently competing priorities—such as maximizing daylight while limiting heat, or balancing flood resilience and water lamination features with budgets—these tools reveal previously inaccessible design strategies, with precision and transparent, replicable and demonstrable rationale.

Digital techniques increasingly leverage and modernise climate-responsive vernacular solutions — for example, wind towers, stilted homes, and mashrabiyas — optimised via algorithmic analysis. Digital twins — virtual models fed with sensor data — allow virtual stress-testing and targeted retrofits in both new and existing buildings. AI and sensor networks support predictive maintenance, identifying stress conditions before they escalate. Advanced control systems can automatically adjust solar protection, cooling, and dynamic façades for heatwaves or storms, allowing buildings to learn from experience and progressively improve.

AI, sensing, and parametric design are rapidly reshaping adaptive architecture and are likely to be the defining factor in climate adaptive design in the next years – despite some current practical barriers –'black box' algorithms that limit practitioner trust, fragmented data, and still comparatively high development and computing costs.

>> As tools become more affordable, standards improve, and performance-based policy rises, digital and AI-driven approaches will likely play a defining role in how the building value chain conceives, delivers, and maintains climate-resilient assets.



Printscreen of parametric design solutions applied to resilience and adaptation at massing stage
© Arup, 2025

Designing for uncertainty:
Insights into the practice

Building codes are gradually integrating climate change considerations, if at a measured pace. Both prescriptive and performance-based design can integrate future climate models to determine design values, although performance-based design offers a degree of flexibility. Nonetheless, there is an urgent need to accelerate the revision of building codes to more accurately reflect the evolving realities of climate change.

Recent global assessments confirm that building codes update cycles lag behind the pace of climate change and still show limited integration of forward-looking climate projections. Most codes continue to rely on historical baselines that no longer represent current or projected conditions.

In this context, practitioners increasingly use downscaled CMIP6 climate projections to bridge the gap, applying forward-looking scenarios to inform design. The responsibility falls to designers to identify, validate, and apply climate data that regulatory frameworks have yet to formalize. Within performance-based environments, designers can substitute CMIP6-derived projections into compliance frameworks, offering flexibility to evaluate compound hazard interactions and conduct scenario analysis. However, beyond requiring sophisticated modelling and specialized expertise, this designer-driven approach imposes additional liability on practitioners operating outside explicit code provisions and demands regulatory capacity to assess non-prescriptive submissions.

Both prescriptive and performance-based pathways can, in principle, incorporate forward-looking climate data, yet neither ensures resilience under deep uncertainty, and both face significant implementation challenges.

Given the slow pace of code evolution and the irreducible uncertainties of a scenario-dependent future, however, practice may need to transition toward a hybrid model. Such an approach would integrate modular, upgradable components—such as reconfigurable façades and tunable thermal systems—with operational continuity protocols that accept managed performance degradation. Continuous monitoring and feedback loops would allow real-time adjustment of design assumptions throughout a building's lifespan.

Regulatory frameworks will likely need to evolve in parallel by standardizing and distributing downscaled climate projections, adopting "living" codes with rolling updates, and embedding adaptive performance criteria that prioritize operational resilience under deep uncertainty.

>> The building design and construction value chain may have to evolve to embrace the unpredictable trajectories of a changing climate through hybrid models that couple compliance with an adaptive, flexible approach to future buildings.

Building code compliance

The Federal Emergency Management Agency (FEMA) has conducted research showing that stronger building codes significantly reduce damage from natural disasters, especially in high-risk areas like Florida. These improvements in construction standards—such as better wind resistance, structural reinforcement, and elevation requirements—can directly lower insurance payouts and disaster recovery costs.

Economic perspective

FEMA has quantified that every dollar invested in code-compliant construction saves multiple dollars in future disaster losses—sometimes cited as $11 in savings for every $1 invested (according to FEMA's "Mitigation Saves" study in collaboration with the National Institute of Building Sciences).

Adaptation and the value-chain of buildings

Adapting buildings to climate change should be in everyone's interest. Yet, full scale streamlined adaptation-thinking is still in the making. Beyond regulatory and market incentives, multiple stakeholders in the building value chain must actively collaborate to address systemic barriers and integrate resilience and adaptive solutions as a key driver in their work – from investment planning to insurance. (Arup, 2025)

Stakeholders

Investor	Regulator	Designer	Contractor	Owner	Tenant Asset Manager	Insurer
Pinch Points						
– Confidence in climate data to make adaptive investing decisions – Need to maximise returns – Short-term gain	– Requires investments but also need to increase resilience of stocks – Inertia – Political cycles	– Need to design for resilience uncertainty – Work with outdated codes – Satisfy client – Contract-timeframes	– Cost and time of additional requirements – Challenges in building for climate specifications – Short-term gain, long-term reputation	– Need to reduce costs – Need to increase resilience of their assets / reduce downtime – "I am insured, so what?"	– Need to be able to afford – Has interested in a safe fruition of the asset with no downtime	– Confidence in risk information – Issues of insurability – Premium vs disclosures

Contractual misalignments
Timeframe misalignments
Technical issues
Conflicting interests
Different roles along the life-cycle

Adaptation interruption

Green infrastructure © Chuttersnap | Unsplash

Solutions for adaptation:
Insights into the contribution of the construction solutions' sector

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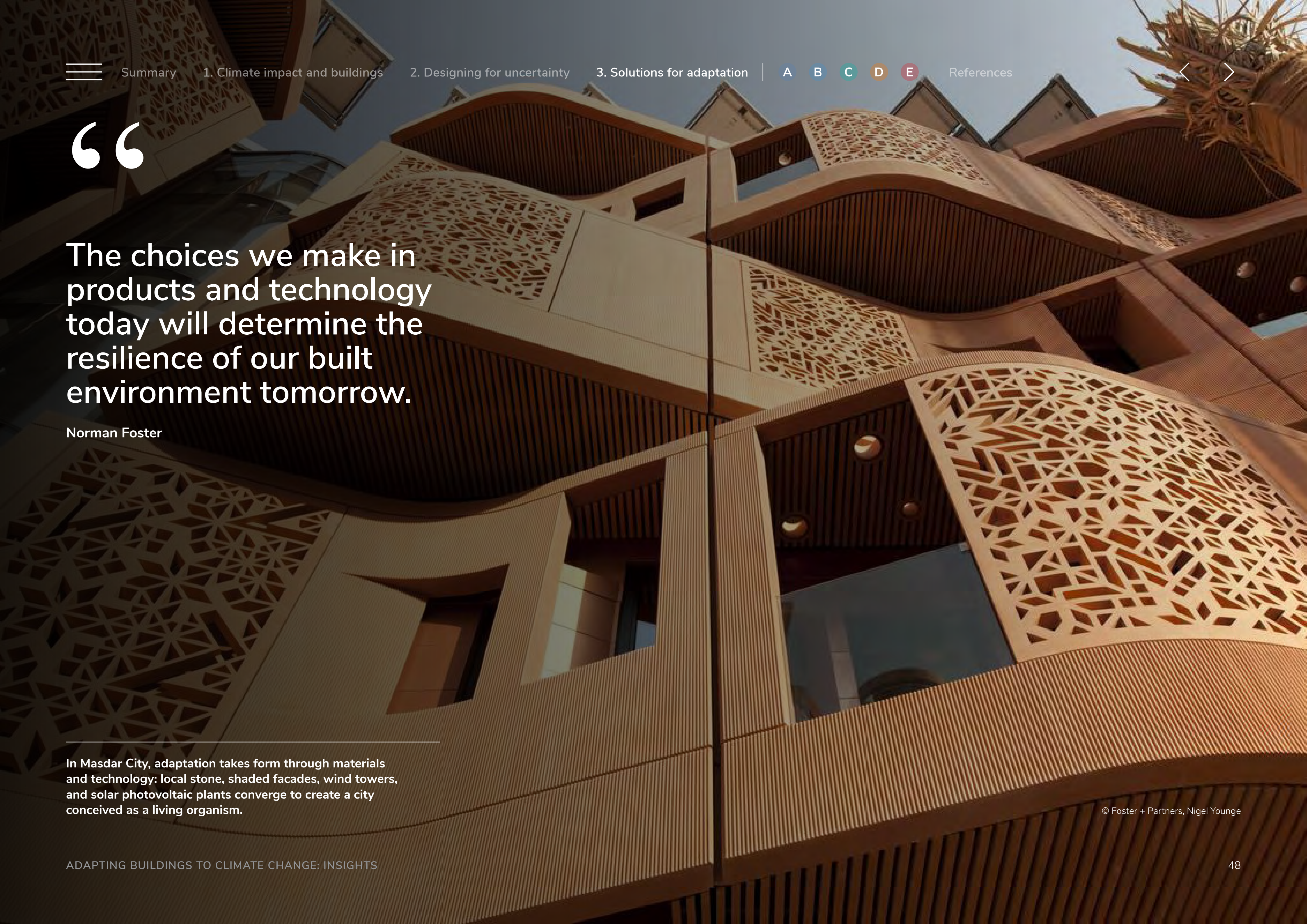

> “The choices we make in products and technology today will determine the resilience of our built environment tomorrow.
>
> **Norman Foster**

In Masdar City, adaptation takes form through materials and technology: local stone, shaded facades, wind towers, and solar photovoltaic plants converge to create a city conceived as a living organism.

Solutions for adaptation:
Insights into the contribution of the construction solutions' sector

The choice of products and systems is a critical aspect of design for adapting buildings. In this chapter, we present five groups of solutions applicable to building' envelopes and sites to reduce risks and increase resilience.

- Market response to the needs of climate adaptation: a) hazard-specific products b) enhanced performance of existing solutions c) rebranding without reinvention

- Solutions nowadays have evolved from individual products to systems and from specifications to performances criteria: this is more appropriate to deal with a) dynamic climate b) multi-hazard

- Leveraging building envelopes and sites for climate adaptation: The first lines of response to multi-hazard

A	B	C	D	E
Thermal Envelope Systems	Solar protection systems	Green building envelopes and green infrastructure	Heat-Reflective and Stormwater-Permeable Surfaces	Enhanced-resistance protective system

- Main hazards addressed include heat waves and extreme temperatures; wildfires; flood and heavy rain; extreme winds and storms

A B C D

A E

C D E

E

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Solutions for adaptation

Insights into the contribution of the construction solutions' sector

The adaptation and resilience market is no longer a future possibility but a fast-growing, high-impact opportunity. The building products industry is responding to the challenges of climate adaptation primarily by showcasing, optimising or repositioning existing products and technologies to meet emerging demands, rather than focusing entirely on new climate-adaptation-specific solutions.

The demand for climate-resilient building products and systems is rapidly increasing, as public and private stakeholders recognise the growing impact of heat waves and extreme temperatures, flood and heavy rains, wildfires, and other extreme events. In response, suppliers in the building product industry are reshaping their positioning and offer strategies to address these evolving climate risks through three main approaches, each reflecting a distinct level of innovation, effectiveness, and market maturity, that are likely to evolve differently across regions:

> Hazard-Specific Products: Some suppliers are broadening the availability and market visibility of products built to withstand distinct climate hazards, such as hurricane shutters, flood barriers, and fire-resistant panels. Originally developed for niche or extreme conditions, these solutions are now achieving wider commercial uptake. This trend is particularly pronounced in the United States, where heightened consumer awareness and localized climate risks are accelerating adoption compared to Europe or India.

> Performance Improvement of Existing Products for Resilience: In other regions, particularly Europe, the prevailing strategy focuses on re-engineering existing products to comply with emerging performance requirements. Instead of introducing entirely new product lines, suppliers are upgrading mainstream materials to deliver enhanced climate adaptive performance — among them hail-resistant shingles, reflective coatings, and solar control glass.

> Rebranding Without Reinvention: In parallel, suppliers are increasingly employing rhetorical repositioning. They are presenting their products as climate-resilient through marketing narratives and eco-labelling, often without substantial modifications to underlying performance. While this approach carries the risk of greenwashing, it underscores the expanding market demand for climate-aware solutions.

Additional emerging directions include a growing interest in modular and prefabricated systems, which can be rapidly deployed in post-disaster contexts or in climate-vulnerable areas.

>> These directions represent a promising frontier for aligning products choice with long-term climate mitigation and adaptation goals.

Climate-Resilient construction investment market

Climate adaptation is no longer a niche. From an economic standpoint, it was long seen as a costly add-on. Currently, clear evidence of its positive return on investment (ROI), combined with the rising costs of climate-related impacts, regulatory momentum and growing emphasis on climate-resilient design practices, are making it both a strategic priority and an attractive market opportunity for private investors and the building products industry alike.

The demand for climate adaptation could rise between 0.5 and $1.3 trillion per year by 2030, with climate-resilient building materials leading at 6-8% growth, with façade and insulation solutions leading growth according to BCG, while for UN Environment (UNEP) a ~$28 billion per year will be required in developing countries

Data sources

BCG Investment Opportunities in Climate A&R Market 2025
BCG Sustaining the Private Capital Opportunity in Climate 2025
BCG (2023) From Risk to Reward
Climate Policy Initiative Global Landscape of Climate Finance 2024
Climate Resilience Alliance Can the private sector plug the adaptation finance gap? 2025
EU CSRD and SEC Climate Disclosure Requirements
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Global Resilience Partnership From Risk to Reward: The Business Imperative to Finance Climate Adaptation & Resilience 2023
Grand View Research Green Building Materials Market Analysis (2025-2030)
ICC How to Scale Private Finance for Adaptation and Unlock New Business Opportunities 2025
OECD Climate Adaptation Investment Framework 2024
Research Nester Green Building Materials Market (2026-2035)
UNEP Adaptation Gap Report 2024

Global Investment Scale

Current adaptation finance	**$28** billion globally (2022)
Projected annual investment by 2030	**$0.5-1.3** trillion
Required developing country investment	**$187-359** billion annually
Current financing gap	**95%** Even doubling current flows only reduces gap by 5%

Building Materials Growth Dynamics

Climate-resilient materials CAGR	**6-8%**
Green building materials market	**$346B (2025)** $914B (2035), 10.2% CAGR
Leading segments	Facade and insulation solutions
Structural products	**66%** Market share
Regional leaders	**35%** share in North America. Fastest growth in Asia Pacific

Investment Returns & Value Creation

ROI Range	**$2-15** for every $1 invested in resilience
Economic damage prevented	**$2** trillion losses from extreme weather (2014-2023)
Private sector opportunity	**15-18x increase** Must scale from $30B to $450B-500B by 2030

Market drivers

Regulatory momentum	EU CSRD, SEC climate disclosure requirements
Environmental stress	Extreme weather driving urgent demand
Financial materiality	Investors requiring climate risk integration

Solutions for adaptation

Insights into the contribution of the construction solutions' sector

The design practice and the building products industry are focusing more on systems that offer a wider range of performances rather than individual solutions. This evolution is well suited to address climate uncertainties and the broader range of climate shocks and stresses buildings need to cope with.

The process of selecting products during design increasingly focuses on identifying integrated solutions that work as systems to deliver the required performance across multiple criteria - as diverse as structural behaviour, thermal regulation, moisture and water management, fire resistance, and long-term durability (as illustrated on the following page).

This approach is well suited to address emerging multi-hazards and uncertain future conditions. Rather than specifying products in isolation to address individual challenges, current practice is shifting toward system integration. In this context, the offering of pre-tested, warranted assemblies is also growing — that is, coordinated packages of products and components capable of delivering multiple, synergistic benefits. This evolution, driven by evolving climatic constraints, design practice, research and innovation in the building products industry, enhances the effectiveness of adaptation strategies and the versatility needed to respond to uncertain climatic conditions, while reducing the risk of maladaptation.

A common example in building envelopes is the ETICS system, a widely adopted solution in which insulation panels are combined with pre-tested fixings, and compatible plaster-based finishes, rather than supplied as standalone products. Nature provides a parallel example: a green roof system integrates distinct components — such as insulation, drainage, substrate, and vegetation — to deliver efficiently multiple co-benefits, including mitigation of the urban heat island effect, reduction of stormwater runoff, and improvement of thermal and acoustic performance.

>> The shift toward performance-driven systems of building products unlock market opportunities for climate adaptive integrated solutions.

© Tsubame Architects

Key Performance Criteria for Climate Resilient Products and Systems

Key Performance Indicators are indicated within brackets [ ]

1.

Durability and Longevity

- Resistance to weathering, such as UV radiation, freeze-thaw cycles and thermal shocks [UV and colour stability, resistance to surface degradation, dimensional and thermal stability]
- Protection against corrosion, especially for coastal or flood-prone areas [corrosion resistance classes]

2.

Thermal Performances

- Insulative properties to reduce thermal transfers and energy consumption [thermal resistance]
- Thermal mass, in direct contact with indoor environments, to moderate temperature swings [thermal inertia]
- High solar reflectance products for building envelopes and pavements for reduced heat gain [albedo]

3.

Solar Protection

- Reduction of unwanted solar heat entering the building [Solar Heat Gain Coefficient / g-value]
- Optimization of natural light transmission for visual comfort [Visible Light Transmittance / VLT]

4.

Structural Resilience

- Mechanical resistance, to ensure structural performance under stress [tensile and compressive strength, impact and tear resistance]

5.

Reaction to Fire and Fire Resistance

- Reduced combustibility of products in wildfire-prone zones and low smoke production [reaction to fire classes]
- Products and systems with ability to withstand fire exposure without loss of structural integrity, insulation, or load-bearing capacity for a specified period [fire resistance classes]

6.

Water Resistance, Vapour Control, Permeability

- Waterproof or water-resistant products in flood-prone areas [water tightness, hydrostatic pressure resistance]
- Humidity and vapour control [water vapour diffusion resistance factor]
- Water permeability to support stormwater management and reduce runoff [permeability and infiltration rate, runoff reduction potential]

7.

Environmental Sustainability

- Low embodied carbon products, characterized by reduced Global Warming Potential across their life cycle stages
- High recycled content or bio-based products to reduce carbon footprint and resource depletion
- Locally sourced products to reduce transportation-related emissions
- Easiness of disassembly, repair and replacement
- Modular design and prefabrication for easiness of future upgrades

8.

Cost and Availability

- Total Cost of Ownership (TCO) over the product's lifecycle, to compare more expensive but higher-performing products with less effective alternatives.
- Availability under supply chain disruptions
- Easiness of deployment of the products in local contexts, including labour skills, available tools, and existing construction practices

Cohering Sustainability and Resilience Needs

Achieving high-performance buildings requires greater resilience with minimal environmental impact. At times, these objectives may appear at odds.

Solutions with reduced environmental impact may not always align with robustness targets under extreme weather conditions, which may imply more choice of carbon-intensive solutions, or larger sections with use of more material and resources. Similarly, circularity principles may face challenges when certification and insurability of reused materials may be questioned under this lens.

But contemporary integrated design can help address these tensions, as follows:

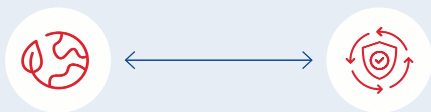
> Resilience and Adaptation extend beyond structural robustness to include adaptability, accommodation, and flexibility. Modular construction systems allow for significant robustness, while accommodation strategies like flood-resistant design often use fewer materials than absolute protection approaches.

> When robustness is critical, innovation in products' research can help reducing traditional trade-offs - such as cross-laminated timber with high compressive strength and sustainability metrics, high-performance low-carbon concrete with significant carbon reduction. These solutions enable enhanced structural performance and prioritise long-term durability, thereby minimizing carbon impacts across the entire building lifecycle.

> Integrated performance optimization creates synergistic benefits. Instead of designing for resilience or sustainability separately, contemporary "Total Design" approaches seek solutions that achieve both simultaneously. For instance, high-performance building envelopes reduce energy consumption during normal operation while maintaining liveable temperatures during power outages. One design solution delivers dual benefits through holistic optimization.

Essentially, contemporary and future resilient buildings with interconnected performance criteria can result from holistic, multidisciplinary collaboration from the earliest design stages, which is the essence of the "Total Design" approach.

>> "Total Design" transcends the robustness-sustainability tension by embracing a Whole Life Cycle Approach — selecting products and systems based on proven durability and low embodied carbon, adopting adaptive maintenance and reuse strategies, and optimizing structural and energy performance across all building lifecycle phases. This ensures long-term resilience while significantly reducing environmental impacts.



Sustainability
Maximizing the efficiency of the system and reducing its impacts on the environment.

Resilience
Balancing efficiency with redundancy of the system to withstand impacts from the environment.

© Sustainability and resilience. Adapted from UNOPS

© Tsubame Architects

Vernacular materials and technologies

Beyond vernacular architecture: from building-scale to city-scale

Globalisation has contributed to the shrinking of vernacular expressions in architecture. Multiple factors are involved, from challenges in standardisation and compliance with building codes, to limited availability of traditional materials, higher initial costs, the loss of local know-how and cultural shifts that favour modern over traditional aesthetics.

Nevertheless, vernacular architecture — often referred to as "architecture without architects" — offers intrinsic sustainable co-benefits, ranging from carbon sequestration when using natural materials, to optimal climate and hazard response that can challenge building norms.

The growing body of literature, especially exploring adaptation, highlights this potential. Interesting solutions and areas of work lie in the hybridisation of these techniques: hempcrete, cob, earthbags, straw bales, bamboo compressed earth blocks, and rammed earth, are often vibrant grounds for innovation.

Scaling up the vernacular and integrating it into today's climate response is a twofold challenge: on one hand, it involves embracing traditional spatial and planning approaches that offer proven resilience to heat and flooding; on the other, it requires creating an enabling environment — through updated regulations, cultural recognition, technical innovation, and hybrid construction methods — to reintroduce vernacular principles into mainstream building practice.

Marialyce Pedersen's house was destroyed in the Eaton Fire, but her cob outdoor kitchen survived. Altadena, California, U.S. January 20, 2025. © REUTERS / Fred Greaves

Post-wildfire cob reconstruction

Cob and similar earthen materials offer high fire resistance due to their non-combustible, dense makeup. Tested walls over 150mm thick withstand 1,090°C for 3–4 hours, keeping the unexposed side under 22°C. With no combustible parts or mortar joints, cob resists ignition and flame spread — recognized in the 2021 International Residential Code. This makes it a strong option for fire-safe rebuilding in post-wildfire California.

Erden Pure Walls, 2021 New European Bauhaus winner. © European Union

Heat-wave response through earthen buildings

Simulations on residential buildings — conducted in the US — show that earth-based walls can reduce annual hours of thermal discomfort by 25–70%, thanks to their ability to regulate heat and moisture. These systems significantly stabilize indoor temperatures year-round, outperforming conventional walls in all tested U.S. climates when paired with passive design strategies.

Resilient floating homes in Bangladesh, project winner of the RISK Award Trophy 2019. © University of Dundee / MunichRe Foundation

Amphibious bamboo architecture

Bamboo is increasingly in demand — at times critically so — due to its exceptional natural tensile strength and rapid renewability. Amphibious bamboo architecture offers a compelling intersection of tradition, innovation, and biomimicry, with applications now being explored across diverse contexts, from Europe to South Asia.

© Tonny Huang | Unsplash

Solutions for adaptation

Insights into the contribution of the construction solutions' sector

The building envelope and the site offer the first and most effective layer of response against multiple, overlapping climate hazards. In these primary environmental interfaces there is a wide range of products and systems that combined contribute to design new buildings, or retrofitting existing ones.

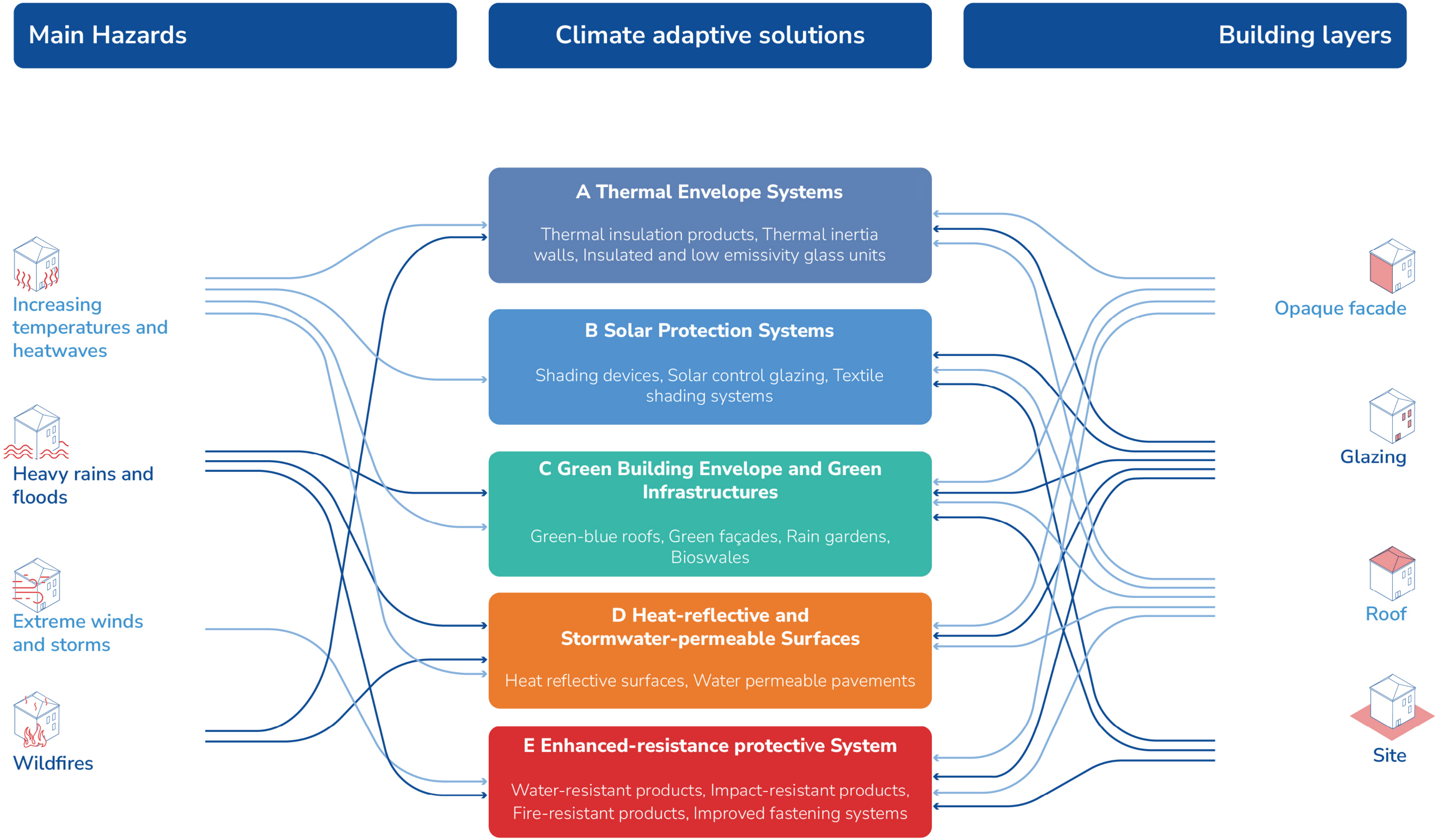
A wide range of climate-adaptation solutions is available for the building envelope — encompassing opaque façades, glazing, roofs, and below-ground walls and slabs — as well as for the site, meaning the immediate external areas surrounding the building.

Products and systems can be selected and combined to address multiple hazards while embedding core principles of resilience: robustness, adaptability, and flexibility.

Together, these solutions support overall design adaptation objectives such as indoor and outdoor thermal control under different future climate scenarios, water and flood management, in the event of peak events and extremes, mitigation of extreme wind effects, and reduction of fire risk.

In the next page the diagram allows for multiple reading entries: starting from the main climate hazards considered in this document or from five key areas grouping a wide range of solutions. Each group describe the range of solutions available, their key benefits for adaptation and co-benefits for sustainability, market penetration in Europe, the US and India and relevant examples.

- A — Thermal envelope systems (A) enhance indoor comfort under heat waves and extreme temperatures, combining robustness and adaptation across opaque façades, glazing, and roofs.
- B — Solar protection systems (B) provide robust defence against intense solar radiation, reducing overheating in glazing, roofs, and site areas.
- C — Green building envelopes and green infrastructure (C) act as flexible, adaptive nature-based strategies that deliver multiple benefits, from mitigating heat waves and extreme temperatures to managing floods and heavy rain, and can be integrated into façades, roofs, and site landscapes.
- D — Heat-reflective and stormwater-permeable surfaces (D) cool down urban areas and manage excess water, offering both robustness and adaptation to heat waves and extreme rainfall through application on roofs, façades, and site pavements.
- E — Enhanced-resistance protective systems (E) are robust measures designed to withstand extreme events, from wildfires to high winds and storms, strengthening opaque façades, glazing, and roofs.


Main Hazards
Climate adaptive solutions
Building layers
Increasing temperatures and heatwaves
Heavy rains and floods
Extreme winds and storms
Wildfires
A Thermal Envelope Systems
Thermal insulation products, Thermal inertia walls, Insulated and low emissivity glass units
B Solar Protection Systems
Shading devices, Solar control glazing, Textile shading systems
C Green Building Envelope and Green Infrastructures
Green-blue roofs, Green façades, Rain gardens, Bioswales
D Heat-reflective and Stormwater-permeable Surfaces
Heat reflective surfaces, Water permeable pavements
E Enhanced-resistance protective System
Water-resistant products, Impact-resistant products, Fire-resistant products, Improved fastening systems
Opaque facade
Glazing
Roof
Site

A. Thermal Envelope Systems

Fostering summer comfort in a warming climate

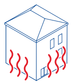
Climate adaptation brief

While thermal envelope systems have been traditionally associated with winter warmth, they can be extremely helpful in hot climates, especially with rising global temperatures. This requires a holistic approach, considered alongside ventilation, solar protection and vapour control, to be effective and mitigate the risk of maladaptation.

Thermal envelope systems contribute to reduce indoor temperature fluctuations, lowering energy demand for heating and cooling, improving thermal comfort, and reducing thermal stress on building structures.

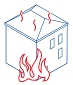
Many buildings still rely on traditional construction methods without layered thermal design and with thermal bridges. Given historical, economic, and policy constraints, much of the housing stock remains poorly insulated and exposed to extreme temperatures – highlighting the urgent need for targeted building retrofit.

Main hazards addressed



A B C D

Heat waves and extreme temperatures



A E

Wildfires

Application parameters

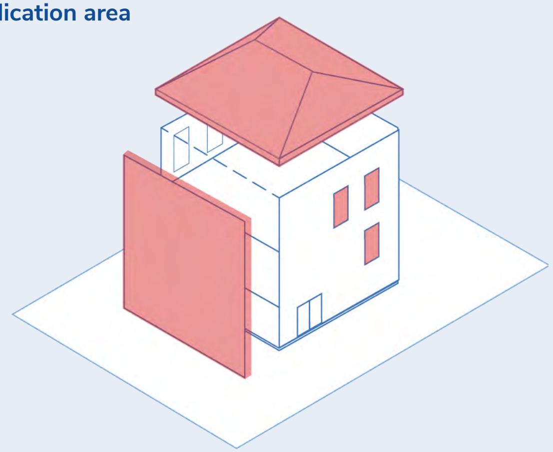
Thermal insulation products and insulated and low emissivity glass units are both effective solutions to mitigate the conductive heat transfer through the building envelope. They regulate heat exchange between indoor and outdoor environments in both directions, preventing heat loss in cold climates and limiting heat gain in hot climates when the space is conditioned, thereby reducing heating and cooling loads.

These systems are more effective the greater the temperature difference (ΔT) between the indoor and outdoor. In contrast, modifying the solar-control coating would likely have a more significant impact.

Combining thermal insulation products with high thermal inertia wall elements is an effective strategy to buffer temperature fluctuations. The thermal inertia addition allows the walls to absorb and store heat when temperatures rise and to release it when they fall. When these massive elements are in direct contact with the indoor environment, they moderate surface temperature variations and dampen indoor temperature swings.

Thermal resistance (m^2K/W)	The ability of the building envelope to limit heat transfer depends on its thermal resistance. Insulation products with lower thermal conductivity (λ) can achieve the same performance with a thinner layer.
U-value (W/m^2K)	Double glazing reduces heat transfer compared to single glazing, lowering U-values from around 5.7 W/m^2K (single pane) to 2.8–3.0 W/m^2K. Low-emissivity coatings and gas-filled cavities could provide further reductions to U-values, reaching 0,8-1,2 W/m^2K and even until 0,5-0,6 W/m^2K for best triple glazing.
Thermal lag (h)	Thermal inertia walls can buffer temperature fluctuations by delaying heat transfer. This thermal lag reduces peak indoor temperature swings, decreasing reliance on mechanical cooling in climates with large day-night variations.

Application area



A1. Thermal insulation products

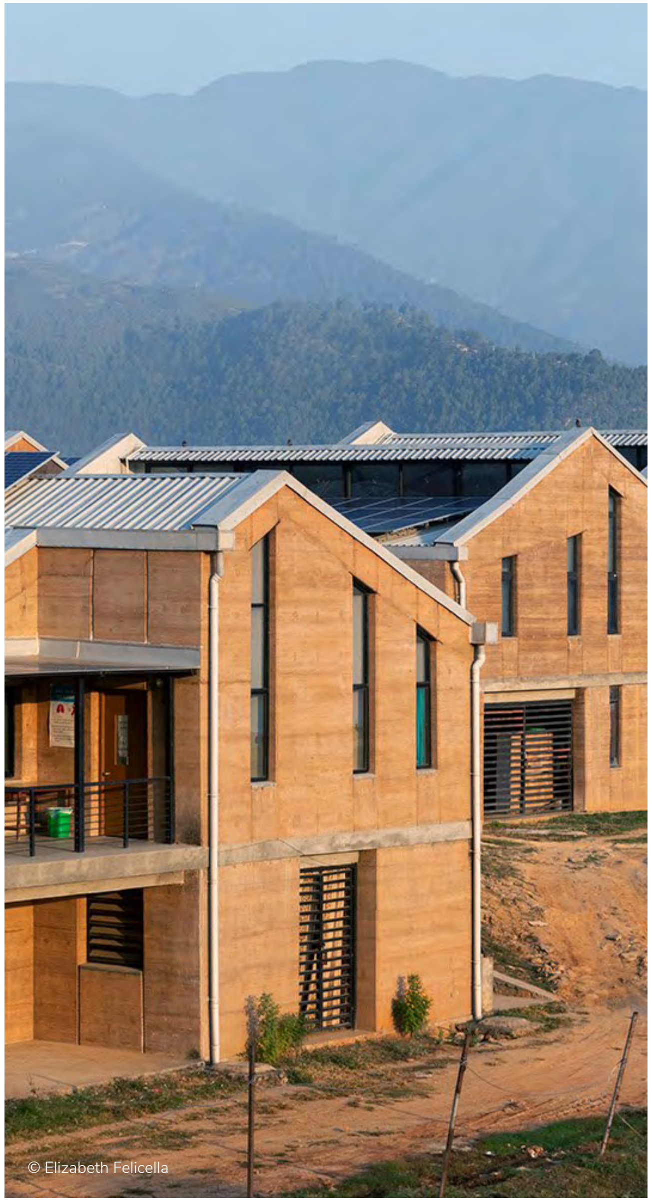
Opaque façade
Roof

A2. Thermal inertia walls

Opaque façade

A3. Insulated and low emissivity glass units

Glazing


© Elizabeth Felicella


© Arup

←— **Bayalpata Hospital**

Location: Achham (Nepal)

Designers: Sharon Davis Design

Building typology: Healthcare

Key adaptive solutions: Thermal Envelope Systems | Solar protection systems

One of its main strategies was the use of soil excavated from the site itself, employed in the rammed earth walls. This traditional technique reduced the use of imported materials and promoted a more local and affordable construction process. The rammed earth walls provide significant thermal mass, which, along with the building's orientation, layout, and roof geometry, helps stabilize indoor conditions against the climatic variations of the mountainous environment. Except for the operating room, which requires mechanical control, the entire building remains comfortable through passive heating and cooling strategies supported by cross-ventilation, roof overhangs, and natural daylighting.

—→ **1271 Avenue of the Americas**

Location: New York, NY (USA)

Designers: Pei Cobb Freed & Partners

Building typology: Office Tower

Key adaptive solutions: Thermal Envelope Systems

The project revitalises a mid-century modern icon through a complete replacement of its façade with a new unitised curtain wall system integrating thermal breaks and low-emissivity insulated glass units. This high-performance envelope increases the vision area by 50% while maintaining the original architectural proportions. Combined with improved thermal insulation, it reduces the building's overall energy consumption up to 40% relative to the current building, achieving LEED Gold certification. The intervention demonstrates how thoughtful recladding can extend the life of historic towers and align them with 21st-century sustainability and comfort standards.

A. Thermal Envelope Systems

Market Overview and Regional Dynamics

In Europe, policies such as the Energy Performance of Buildings Directive (EPBD), the Energy Efficiency Directive (EED), and the Renovation Wave Strategy are driving a growing demand for high-performance construction products — including advanced insulation products, low-U-value glazing, airtight sealing systems, and bio-based building components — across the continent.

India, facing rapid urban expansion and extreme heat in many regions, is beginning to integrate better insulation practices, particularly in high-end and institutional buildings. However, the broader market still relies heavily on constructions that offer poor thermal performance. Insulated Glass Units (IGUs) are gaining traction in urban commercial buildings, especially in glass-heavy architecture, but cost and availability remain barriers for wider use. That said, growing awareness around energy-efficient building design, spurred by initiatives like the Energy Conservation Building Code (ECBC) and the Green Rating for Integrated Habitat Assessment (GRIHA), is gradually shifting the market.

In the United States, the market is varied but steadily evolving. It benefits from growing demand for energy-efficient buildings and strong regulatory support, such as the International Energy Conservation Code (IECC) and the California's Title 24 energy codes, with a focus on a broad range of insulation products like fiberglass and foam, alongside mature IGU technologies, especially in commercial and residential sectors. Despite variations in energy code adoption and advancement across states, with some lacking a state-wide code, other factors, such as product costs, return on investment (ROI), and tariffs, also influence the market.

	A1. Thermal Insulation Products	A2. Thermal inertia walls	A3. Insulated & low emissivity glass units
Europe			
	Very mature market. Most commonly used products are mineral wool, EPS/XPS and PU. Increasing use of bio-based products (e.g. wood fiber, cork). Example of suppliers Weber, Isover, Knauf, Rockwool, Kingspan, BetonWood, Thermalfleece, URSA, Soprema, Foamglas, Thermofloc, Steico, Gutex, La Sureda Cork, Sofalca, Aerobel	Widely used, especially in Mediterranean countries where masonry (concrete, bricks) and stone buildings are traditional. In recent years, prefabricated systems and natural products, such as rammed earth, straw bales, have seen rapid expansion. Example of suppliers Leca, Termoarcilla, Porotherm, Ytong, Hebel, IsoHemp, HempFlax, Fetdeterra, Bioterre, Terlian	Double glazing with low-e coatings is a standard in most new buildings. Triple glazing in colder areas is common, driven by voluntary energy performance standards such as Passivhaus. Example of suppliers Saint-Gobain, AGC, Guardian, Pilkington, Schott, Glass X Notable IGU Transformers Tvitec | Cricursa, PRESS GLASS, Sedak, Vandaglas Eckelt
India			
	Available but less commonly used in residential buildings. Mostly found in commercial buildings and high-end residential with insulation products such as EPS/XPS, glass wool and stone wool. Example of suppliers Rockinsul, Siderise, Twigasul, Knauf	Inherent in older or vernacular architecture (thick brick/stone walls) in hot-dry regions but less emphasized in modern construction. Example of suppliers Auroville Earth Institute, Earth Blocks India Pvt. Ltd., Gohemp Agro, BOHECO, Magicrete, Biltech	Overall double-glazing is minor compared to single-glazing, but adoption is growing rapidly in metros, tier-1, tier-2 and tier-3 cities. Regulated by ECBC (varied enforcement). Example of suppliers Gujarat Guardian, Asahi Glass, Magnum Tuff India Pvt Ltd, Fuso, Saint-Gobain
United States			
	Widely available. A mature market with a wide range of products like fiberglass, mineral wool, foam boards, spray foam, cellulose. Regulated by ASHRAE, IECC. Example of suppliers Owens Corning, Johns Manville, CertainTeed, Knauf Insulation, Rockwool	Available, typically made of concrete, ICF blocks, adobe, or masonry, are used in hot-arid climates and energy-efficient homes. Their adoption is growing in hurricane-prone areas (e.g., Florida) and discussed in wildfire regions (e.g., California), though permitting can be a barrier. Mass timber has also gained attention recently. Example of suppliers Rammed earth works, SIREWALL, Adobe Building Systems, Earth Block Inc, Structurlam, SmartLam North America, Hempcrete	Double glazing is common in commercial buildings and increasingly in residential. Regulated by IECC, ASHRAE. Example of suppliers Cardinal, Guardian, Viracon, Saint-Gobain

Disclaimer: The suppliers listed in this table are provided for illustrative purposes only. The selection is informative and non-exhaustive, and the companies are not ranked or endorsed in any way. The list aims solely to represent examples of suppliers active in the regions analysed (United States, India, and Europe) and does not imply any preference, recommendation, or certification by the authors.

A. Thermal Envelope Systems

Co-benefits: Integrating low-carbon, high-performance thermal solutions

Thermal envelope systems improve heat regulation, acoustic insulation, fire resistance, and water tightness, while low-carbon and low-emisison products add environmental benefits.

Beyond beneficial effects in managing thermal flux across the building envelope, thermal envelope systems can offer enhanced performance characteristics, including improved acoustic insulation, high fire reaction and resistance, and reduced water permeability, boosting resilience against additional hazards such as wildfires, flood, and heavy rain.

In addition, integrating low-carbon building envelope products with high recycled or biobased content can bring environmental co-benefits.

>> Some materials, such as Closed-Cell Spray Polyurethane Foam (ccSPF), Extruded and Expanded Polystyrene (XPS and EPS) and foam glass are waterproof, well-suiting flood-resilient applications. However, not all the products made from these materials are non-combustible, as their fire reaction can vary.

Non-combustible solutions like mineral wool insulation, laminated glass with fire-rated interlayers and frames, Autoclaved Aerated Concrete (AAC) walls further improve fire safety in the building envelope.

© Hotel Mas Torre del Marques in Spain. Interior Mediterranean climate with hot summer. Vogue

A. Thermal Envelope Systems

Integration in the broader design processes

Reduction of thermal bridges

Applying insulation to the exterior surfaces of a building helps to create a continuous thermal barrier that minimizes thermal bridges and related heat losses. However, external insulation may not be allowed in heritage buildings, retrofitted façades, or dense urban areas. In these situations, internal insulation becomes a viable alternative, although it reduces the usable floor area. It also requires careful design to mitigate the risk of interstitial condensation — particularly when the existing wall has low breathability or lacks vapor control layers — and to manage thermal bridges at floor slabs, window reveals and partition junctions.

Optimising thermal inertia walls

Massive walls with thermal inertia tend to be less effective in climates with small diurnal temperature variations or high humidity, where limited night-time cooling reduces their ability to release stored heat. To maximize their performance, these systems should be integrated with external insulation, solar shading, controlled ventilation, and effective moisture management. Optimal results are achieved when the thermal mass is exposed to the interior, allowing it to absorb indoor heat gains, while external insulation protects the structure from daytime heat. Nighttime ventilation is required to cool the mass and restore its thermal buffering capacity, and a balance must be considered in situations where this cooling cannot be achieved, such as during extended periods of hot nights.

Wind-driven rain vulnerability

ETICS (External Thermal Insulation Composite Systems), an external insulation system designed to boost a building's thermal performance, might be vulnerable to wind-driven rain, mold, and even structural collapse during storms. These risks are further exacerbated by water saturation, weakening of fixings, and the absence of a ventilation gap. In contrast, ventilated rain screen systems are mechanically anchored, featuring an air gap and durable exterior cladding.

Integrating insulation with proper moisture-control design

Improving insulation often increases airtightness, but without adequate ventilation, it can trap heat and moisture, leading to poor heat dissipation, condensation, mold, and unhealthy indoor air. This is especially challenging in retrofits, where constraints may restrict ventilation improvements and moisture management. Ensuring buildings are both insulated and ventilated properly, using smart vapor barriers, integrating air cavities, such as in raised access flooring or in attics, and choosing moisture-resistant insulation products, are essential to avoid issues like moisture buildup. For example, the ETICS system needs to be engineered with the appropriate vapour permeability requirements to dry out.

Triple vs double glazing units

While triple glazing effectively reduces the U-value, minimizing heat transfer, it may offer limited benefits in hot climates, where metrics like Solar Heat Gain Coefficient (SHGC) or solar factor play a more decisive role in cooling performance. In such contexts, the marginal gains in energy savings may not justify its use. Additionally, triple glazing is heavier, more expensive, and associated with higher embodied carbon, making it a solution best suited to cold climate applications where heat retention is a priority.

Building Smarter:

Innovations and future trends

Next-Generation Products and Technologies

Looking ahead, the new frontier of **innovation** lies in the development and the integration of **Phase Change Materials (PCMs)**, which offer dynamic thermal regulation by absorbing, storing, and releasing heat during phase transitions. **Aerogels**, ultra-lightweight and extremely low thermal conductivity products, may be in transparent and flexible forms, and **Additive Manufacturing**, such as 3D printing of earth-based walls, enables fine-tuned control over wall density, allowing for customized thermal inertia and even integrate thermal mass and insulation layers in a single printing process.

A variety of performance designs with drywall systems

Drywall systems, especially in prefabricated and modular forms, offer easy-to-install solutions that support circularity and end-of-life reuse in modern construction. To fully unlock their potential, careful attention must be given to the design of thermal and structural joints — crucial not only for maintaining thermal efficiency and structural integrity but also for enabling disassembly and reuse. Achieving high thermal performance requires pairing drywalls with advanced insulation products, while ensuring the system withstands mechanical stresses, impacts, wind loads, and moisture.

B. Solar protection systems

Protecting building from intense solar radiation

Climate adaptation brief

Solar protection systems are designed to limit solar heat gain while allowing natural light to pass through, making them essential for energy-efficient buildings in warm and hot climates.

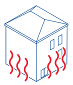
They are mainly applied to glazed area of the building envelope and external liveable areas, such as roof, terraces and external areas.

Solar control glazing offers a first layer of solar defence, upon which other solar protection solutions can be layered to achieve high-performance and climate-responsive buildings. Combining multiple glass coatings, such as low-emissivity, spectrally selective, fine-tunes thermal insulation, solar control, and visual comfort.

By reducing heat absorption from direct solar radiation, these systems enhance the durability and performance of the building envelope exposed to intense solar radiation, as they help reduce thermal stresses on the building fabric.

They can also contribute to reducing heat island effect, lowering the temperature and the heat absorption of building envelope and external areas exposed surfaces and to prevent rain penetration under extreme weather.

Main hazards addressed



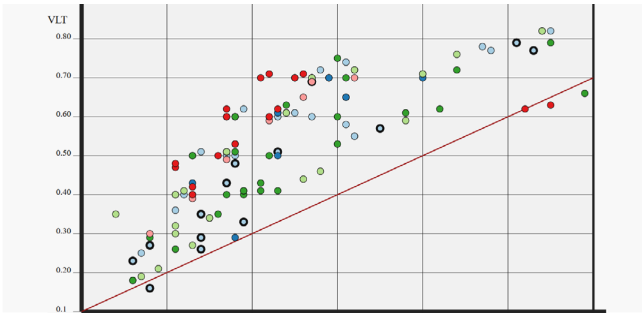
A B C D

Heat waves and extreme temperatures

Application parameters

The effectiveness of solar control systems is quantified through two key parameters: the Solar Heat Gain Coefficient (SHGC) or Solar Factor (g-value), and the Visible Light Transmittance (VLT). Reducing the SHGC (or g-value or solar factor) of solar control solutions (i.e. solar control glazing, possibly complemented by solar shading) minimize the thermal loads entering the building.

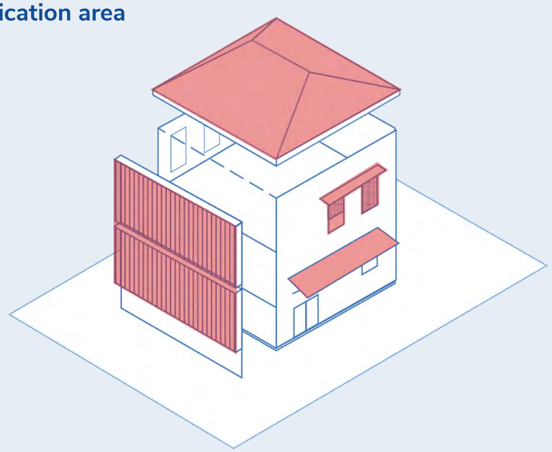
When it comes to solar control glazing, from a solar factor of approximately 0.5 one can already observe a first significant decrease in cooling demands and enhanced indoor thermal comfort. The reduction of the solar factor typically results in a corresponding decrease in Visible Light Transmission (VLT). Latest advancements in coating technologies have made it possible to maintain a favourable balance between solar control and daylighting (selectivity). The choice of the right parameter should be based on specific building characteristics, including among others the building type and usage, location and orientation as well as size of the glazed surfaces. This approach ensures that façade design aligns with both architectural intent and performance objectives.



Glass selectivity graph comparing the VLT and g-value of commercial coatings, Arup 2021

The coloured points refer to different suppliers available in the market.

Application area



B1. Shading devices

Glazing / Roofs (e.g. brise-soleils, adjustable louvers, horizontal overhangs, external blinds, or automated shading systems)

B2. Solar control glazing

Glazing (e.g. selective coating, fritting, electrochromic and photochromic coatings, dynamic glazing)

B3. Textile architectural systems

Site / Roof (e.g. tensile, pneumatic, pre-stressed membrane systems, awnings and other retractable membrane systems)


© Tõnu Tunnel


© Sanjay Puri Architects

← Pelgulinna State Secondary School

Location: Tallinn (Estonia)
Designers: Arhitekt Must OÜ
Building typology: Educational
Key adaptive solutions: Solar protection systems

Pelgulinna State Secondary School in Tallinn, Estonia, is by nature and features expansive glazed façades, the school offers a bright and welcoming atmosphere conducive to learning. Central to its design is the use high-performance solar control glass allows generous daylight penetration (up to 60% light transmission) while effectively limiting solar heat gain (solar factor below 0,30), ensuring visual and thermal comfort throughout the year. By reducing the need for artificial cooling and minimizing heat loss during colder months, the glass supports both energy savings and sustainability goals. The project demonstrates how thoughtful product selection, adapted to local climate conditions and building function, can achieve a harmonious balance between comfort, efficiency, and architectural quality.

→ Mirai House of Arches

Location: Bhilwara (India)
Designers: Sanjay Puri Architects
Building typology: Residential
Key adaptive solutions: Solar protection systems

Mirai is a house specifically designed to face the warm and desert climate of the Rajasthan region in India. To adapt to these extreme conditions, it features a “second skin” that wraps around the interior spaces, reducing heat gain and protecting its inhabitants from the intense summer heat. Through curved volumes and arched openings in its envelope, semi-open and shaded spaces are created around the entire perimeter, with deeper recesses on the façades facing the garden.

These design elements significantly reduce heat entering the interior and provide sheltered outdoor areas for each room, keeping the house cool during the hottest months.

B. Solar protection systems

Market overview and regional dynamics

The market for shading devices, solar control glazing, and textile architectural systems is growing globally, driven by increasing energy efficiency awareness, stringent building regulations, and evolving architectural demands.

Across these regions, the evolution of solar management strategies points to integrated systems that combine passive design principles with cutting-edge products, enabling buildings to dynamically respond to solar exposure.

In North America and Europe, well-established regulatory frameworks and green building certifications push the adoption of advanced shading devices and high-performance solar control glazing, often integrated with smart automation for enhanced comfort and energy savings. Textile architectural systems are gaining traction as flexible, aesthetic solutions in commercial and residential projects.

Meanwhile in India, solar control glazing adoption is growing, pushed by government incentives and green building certifications. It is notably the preferred choice in commercial buildings for solar protection in consideration with daylighting, oudoors views and aesthetics. Solar shading is integrated rather in residential buildings, in the form of balconies, overhangs and elevation elements.

	B1. Shading devices	B2. Solar control glazing	B3. Textile architectural systems
Europe			
	Highly adopted, especially in central and southern Europe.	Very common, especially in energy-efficient buildings.	Highly developed sector; used in large-scale public infrastructure and modern architectural designs.
	Example of suppliers Bandalux, Colt, Griesser, Microshade, Pellini SpA, Warema, STOBAG, Saxun, Verosol, Somfy, Harol, Schüco, Reynaers, Hunter Douglas, Renson	Example of suppliers Pilkington, Saint-Gobain, AGC, Guardian, SageGlass, Glas Trösch GmbH, Arcon, Sefar	Example of suppliers Serge-Ferrari, Taiyo Europe, IASO, Tensoforma, Canobbio, Bat Spain, Mehler Texnologies
India			
	Common in traditional and vernacular architecture with traditional methods used (jalis, chhajjas). Modern mechanical or dynamic systems are still niche.	Available and used in premium commercial and high-end residential projects. Lower penetration in mass housing.	Growing presence in urban infrastructure, especially in airports, pavilions, and high-end commercial applications.
	Example of suppliers RCS Colt, Hunter Douglas, Alumil Systems, Aluform	Example of suppliers Saint-Gobain, Guardian, Vitro, Asahi	Example of suppliers Skyshade, Sprech Tenso-Structures, Serge-Ferrari
United States			
	External shading systems are increasingly common across the U.S., with region-specific applications, from residential overhangs and shutters to commercial louvers and fins, where they also support hurricane protection and advanced façade design.	Widely adopted in commercial buildings, particularly in the South and West where solar exposure is highest. In the residential sector, adoption is slower and more uneven, though it is also most common in those same sunbelt regions.	Available, mainly used in high-profile projects such as in stadiums, airports, and public spaces. Tensioned fabric shade structures are quite common either attached to building, either shading building-adjacent spaces.
	Example of suppliers Hunter Douglas, Draper, Mecho Shade, Kawneer, YKK, Glastec	Example of suppliers SageGlass, Suntuitive, Guardian, Vitro, AGC	Example of suppliers Birdair, FabricTec, Structureflex, International Tension Structures, Dunn

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B. Solar protection systems

Co-benefits: reclaiming indoor and outdoor comfort in hot climates

Solar protection systems enhance outdoor and indoor comfort, reduce the urban heat island effect, enable passive cooling through natural ventilation, and help prevent water penetration during heavy rain.

Beyond the beneficial effect of improving indoor comfort and protecting the building envelope from extreme temperatures, the impact of solar protection systems extends to the urban scale where, as cities grow denser and hotter, passive solar protection becomes more than a design feature.

They boost resilience in the public realm while reclaiming outdoor comfort and reducing the urban heat island effect. For example, high-reflectance fabrics and coatings reflect a significant portion of incoming solar radiation, minimizing heat build-up on surfaces and in the shaded areas below. Additionally, breathable or microperforated membranes facilitate airflow, promoting passive cooling through natural ventilation.

External shading devices with angled surfaces and extended projections, such as overhangs, louvers, and canopies, help prevent heavy rain penetration, acting as physical barriers that divert rainwater away from the building.

Combining multiple solar control coatings applied on glazed surfaces, such as low-emissivity, spectrally selective, block a significant fraction of the solar heat gain entering the building, fine-tuning indoor thermal insulation, solar control, and visual comfort.

Dynamic systems such as movable blinds and dynamic glazing could enable further overheating protection.

© Downtown Zetland project, Australia. External folding louvres shading a terrace. FTI Group

B. Solar protection systems

Integration in the broader design processes

Integrating solar protection systems into the building design

Designing effective solar protection starts with passive strategies – solutions embedded in the building envelope that, while responsive to external conditions, operate independently from mechanical systems and are integral to the architectural fabric. These include design features like overhangs, balconies, and form-shaped shading, as well as solar control glazing, and natural solutions like deciduous trees and green façades. These elements offer savvy design solutions besides enhancing solar protection.

External shading systems block solar radiation before it reaches the building, making them an effective line of protection against radiative heat gain. However, exposed to the elements, they must be durable enough to withstand extreme weather conditions and long-term wear. Also, since external shading often relies on metal frames that add embodied carbon, their use should be carefully balanced. Internal shading devices, such as blinds, shades and curtains, are typically less effective in managing thermal gains, as they only act after solar radiation has entered the building. The use of high reflective products combined with the use of high performing glazing could improve their efficiency.

The orientation of the façade is critical for designing effective solar protection, together with the solar azimuth and solar altitude angles across different seasons. Generally, south-facing façades benefit from horizontal overhangs that block the high-angle summer sun, while east and west façades require vertical louvres to control the lower-angle, morning and afternoon sunlight.

Managing solar reflection risks

Implementing reflective solar protection systems requires precise calibration of material properties and façade geometry to blend solar control with occupant safety. Either glass panels or coated surfaces with high solar reflectance can create unintended "hot spots" on adjacent exterior surfaces. These concentrated reflections may also create safety concerns, including hazardous glare in sensitive areas such as airport runways, and visual discomfort or reduced visibility in the surrounding environment. A promising solution lies in the use of retroreflective products, engineered to redirect solar radiation back toward its source direction with precision. This targeted reflection not only mitigates the formation of localized hot spots but also minimises heat build-up and contributes to lower ambient outdoor air temperatures.

Improved resistance of solar shading systems due to extreme events

As extreme weather events become more frequent and intense, solar shading systems, particularly external dynamic features such as automated roller blinds, shall meet new durability demands. Exposure to extreme winds, hail, storms and UV radiation challenges conventional products and assemblies.

To remain effective and resilient, next-generation shading solutions incorporate impact-resistant products, such as reinforced polymers or laminated fabrics, structurally robust frames, and flexible joints or mounting systems that can absorb movement without damage, complemented by sensors that detect extreme events so that protective measures can be activated to safeguard the systems.

The impact of colour and albedo on solar protection performance

Dark-coloured external shading can inadvertently act as radiators, absorbing and re-emitting heat instead of providing cooling. This issue is common in Mediterranean regions, where dark green awnings are often used as an architectural feature but end up increasing indoor heat. To avoid maladaptation, it is recommended to use highly reflective fabrics and combine white, sun-facing surfaces with darker tones inside. Low-emissivity coatings can further reduce heat radiation, while natural shading (such as trees) should be prioritized over artificial systems.

Building Smarter:

Innovations and future trends

Advanced solar protection technologies

Solar protection systems are evolving fast, blending cutting-edge technologies to tackle heat, light, and energy use.

Electrochromic glass, for example, automatically darkens or clears in response to sunlight intensity, fine-tuning the amount of light and heat passing through the façade.

Adaptive façades with automated louvers, retractable screens, and kinetic shading elements constantly respond to changing conditions, optimizing solar control by adjusting transparency and reflectivity in real time. These systems often integrate cutting-edge smart products, such as thermochromic coatings and shape-memory alloys, that enable façades to react autonomously to temperature and light variations.

Integrating solar panels into shading devices, **building-integrated photovoltaics** (BIPV), turning façades and canopies into energy generators while keeping interiors cool and comfortable. A compelling example is the Solar Leaf pilot project (BIQ House, Hamburg), which goes a step further by combining shading with microalgae bioreactors, producing renewable energy and biomass while actively filtering CO_2 from the air.

C. Green building envelopes and green infrastructure

Nature-based solutions as multiple-benefit strategy

Climate adaptation brief

Green infrastructure (GI) are key elements for significantly reducing the urban heat island (UHI) effect. Reducing paved surfaces limits the effect of overheating. GI also provides cooling effects that enhance thermal comfort for building occupants.

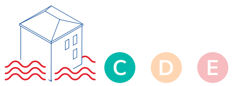
Instead of expanding grey infrastructure (sewers, pipes), nature-based GI elements such as green roofs, rain gardens or bioswales, offer multiple benefits associated with Sustainable Urban Drainage Systems (SuDS).

Nature-based green infrastructure (GI) retrofit solutions are increasingly encouraged through regulatory frameworks and green finance mechanisms. Examples include subsidies for green roofs and walls in urban areas, low-interest loans for retrofitting buildings with permeable surfaces or rain gardens to manage stormwater locally, and funding to develop comprehensive climate adaptation strategies.

While GI solutions must be adapted to each project's site-specific technical and environmental needs, there are a variety of off-the-shelf systems.

Main hazards addressed

Heat waves and extreme temperatures

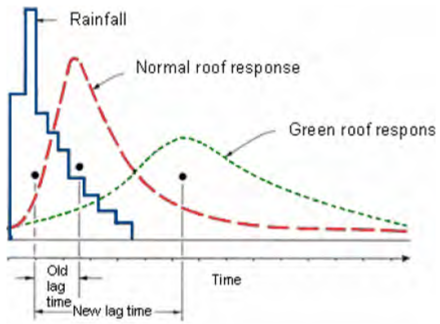


Flood and heavy rain

Application parameters

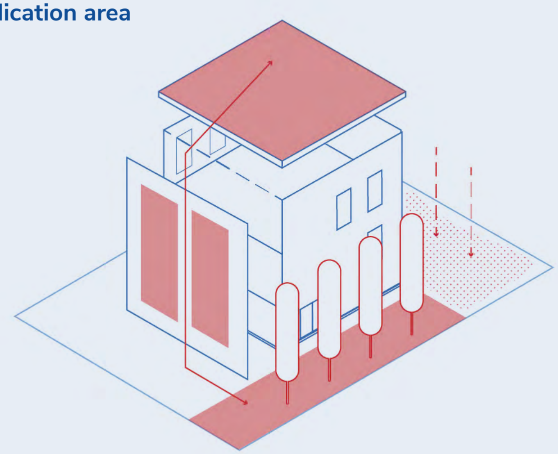
Green roofs help manage and reduce stormwater runoff – especially important on sites with limited space and high amounts of pavement. The primary parameters for evaluating a green roofs' ability to attenuate stormwater are the Runoff Coefficient (Cr), a dimensionless ratio representing the proportion of rainfall that becomes runoff, and the Retention Capacity [measured in mm or L/m^2], the amount of rainfall a system can retain during a storm event. Many studies suggest that green roofs can reduce stormwater runoff in comparison to conventional roofs with volume retention scores in the order of 40–80% of the total rainfall volume. From literature's data it is also evident that a decrease of 60–80% in runoff peak rates is to be expected from a green roof. Generally, the annual retention rate could vary considerably depending on dimensioning, soil type, rain intensity and frequency.

Albedo measures the amount of incoming solar radiation that a surface reflects back into the atmosphere, rather than absorbing and converting it into heat. Typical albedo values for vegetation range between 0.18 and 0.25, depending on plant type/leaf colour. Plants increase the albedo of surfaces exposed to solar radiation. Their cooling effect is a result of the combined impact stemming from moderate albedo rate, high evapotranspiration potential, and the benefits of shading.



Hydrograph to show the increase in lag time after a storm event with green roofs.

Application area



C1. Green-blue roofs

Roofs (e.g. intensive, extensive, semi-intensive)

C2. Green façades

Opaque façades (e.g. vegetated mat wall, cable system, modular living wall, planters with structural support)

C3. Bioswales and Raingardens

Site


© Singular Green / LIFE MyBuildingisGreen


© James Steinkamp Photography

← Colegio Público Gabriela Mistral (Solana de los Barros, Badajoz, Spain) – LIFE MyBuildingisGreen project (LIFE CCA/ES/000088). Executed by SingularGreen

Location: Badajoz (Spain)

Designers: SingularGreen

Building typology: Educational

Key adaptive solutions: Solar protection systems I Green building envelope and green infrastructures

In response to high temperatures and water scarcity experienced in the region, the school carried out a refurbishment focused on Nature-Based Solutions (NbS) to increase building´s resilience while also improving the well-being of the educational community. The intervention included green roofs, vegetated façades, indoor vertical gardens, shading pergolas and permeable pavements. Thanks to these measures, classroom temperatures were lowered, reaching levels below the recommended indoor thermal comfort threshold -27°C- during the school period. The difference between the average temperature of the surfaces with green roofs compared to those without vegetation are 5.4°C. The implementation of these solutions reduced rainwater runoff losses from an average of 13% (without interventions) to just 3% in the improved building. The intervention positioning the school as a benchmark in climate adaptation and educational sustainability.

→ Spaulding Rehabilitation Hospital

Location: Charlestown (United States)

Designers: Perkins & Will

Building typology: Healthcare

Key adaptive solutions: Green infrastructure (Bioretention swales) and green building envelope

The design of the hospital has been strongly influenced by the risks the site is exposed to, such as hurricanes, storm surges, potential coastal flooding and rising sea levels. Large granite blocks act as barrier reefs, deflecting waves and protecting the building. An extensive drainage network quickly disperses floodwaters. To ensure continued operation in the event of flooding, all mechanical equipment has been installed on the roof or upper floors.

C. Green building envelopes and green infrastructure

Market Overview and Regional Dynamics

The market for green infrastructure is rapidly evolving globally, driven by rising urbanization, climate resilience demands, and regulatory momentum.

In Europe, mature policies and robust incentives have fostered widespread adoption, with cities like Copenhagen, Berlin, Basel, Paris, Wien leading in large-scale green roof and façade implementations. Here, stringent stormwater management regulations and ambitious carbon neutrality goals fuel investment in multifunctional green systems.

In India, the green infrastructure sector is still emerging but shows immense potential driven by urgent needs to combat urban heat islands, air pollution, and water stress in cities like Delhi and Bangalore. Innovative pilot projects combining green roofs and bioswales are increasingly supported by government initiatives and international climate funds, although widespread adoption faces challenges including funding, technical expertise, and maintenance capacity.

In the United States, green-blue roofs have gained some traction in cities like New York and Chicago, though adoption remains limited by upfront and ongoing maintenance costs. There was a surge of interest in green roofs about a decade ago in the U.S.; while the buzz has since faded, uptake has remained relatively steady, though economic viability continues to be a challenge. Green façades, though less widespread, are emerging in dense urban areas such as San Francisco and Portland, where they contribute to energy efficiency, air quality, and biophilic design in LEED- and WELL-certified buildings. Meanwhile, bioswales and rain gardens are among the most widely adopted green infrastructure elements, supported by public-private partnerships, green financing, and regulatory mechanisms such as stormwater fees and mandates to reduce combined sewer overflows (CSOs).

	C1. Green-blue roofs	C2. Green façades	C3. Bioswales and Raingardens
Europe	Extensively adopted in both extensive and intensive configurations. Example of suppliers Sempergreen, ZinCo, NatureGreenRoof, Le Prieuré Vegetal i.D., Soprema, Bauder, Nophadrain, Sika	Highly integrated in eco-friendly designs, these living walls often feature automated irrigation and monitoring systems to maintain plant health and optimize energy efficiency. Example of suppliers Helix, Green Fortune, Paisajismo Urbano, Soprema	Widely implemented in cities with stricter requirements for sustainable drainage planning. Example of suppliers Layfield Group, ACO Group, Hydro International, Polypipe, Hauraton, GreenBlue Urban, Otto Graf; however built typically as part of general contractor scope and complimented with elements from specialists as necessary
India	Slowly making its way into the urban landscape, green roofs are chiefly seen in pilot projects and upscale developments aimed at sustainable urban renewal. Example of suppliers Ecogreen Landscape Technologies, Strata	Emerging as a trend in high-end commercial and institutional architecture, green façades are beginning to appear in urban settings, primarily through early pilot projects as part of evolving sustainable building practices. Example of suppliers ELT India, ZTC International	Gaining interest in emerging urban centers facing water management challenges, these systems are being explored through conceptual studies by specialized local landscape and environmental design firms. Example of suppliers Built typically as part of general contractor scope and complimented with elements from specialists as necessary.
United States	A well-established component in commercial construction and an emerging feature in residential design. Example of suppliers ZinCo Green Roof Systems, Green Roof Solutions Inc., Carlisle Syntec Systems, Tremco Roofing & Building Maintenance, LiveRoof, Rooflite, Sempergreen USA, W.R. Meadows	Increasingly popular for improving energy performance and building aesthetics, green façades are now common in forward-thinking commercial and residential projects. Example of suppliers Sempergreen USA, LiveWall, Gsky Plant Systems	Frequently integrated in sustainable urban projects and commercial developments. Example of suppliers Filtrexx, AQUALIS; however, built typically as part of general contractor scope and complimented with elements from specialists as necessary

Disclaimer: The suppliers listed in this table are provided for illustrative purposes only. The selection is informative and non-exhaustive, and the companies are not ranked or endorsed in any way. The list aims solely to represent examples of suppliers active in the regions analysed (United States, India, and Europe) and does not imply any preference, recommendation, or certification by the authors.

C. Green building envelopes and green infrastructure

Co-benefits: harnessing nature-based solutions for climate, health and biodiversity

1.

Flood risk reduction

Green-blue roofs, bioswales and rain gardens provide low-impact methods for catching, treating and reusing stormwater at the first point-of-contact.

2.

Improve Air Quality

Vegetation on façades helps filter airborne pollutants such as particulate matter and nitrogen oxides.

3.

Lower Energy Consumption

GI provides a natural form of insulation on roof / facades. By utilizing the thermal mass effect, shading surfaces from direct sunlight, and enhancing evapotranspiration to dissipate heat naturally, vegetation helps stabilize outdoor temperatures – and in turn indoor as well.

4.

Increase Roof Lifespan

A vegetated roof layer protects the waterproofing membrane from UV radiation and temperature fluctuation , while also shielding the underlying structural elements.

5.

CO_2 Absorption

Plants absorb carbon dioxide through photosynthesis, contributing to carbon sequestration and climate mitigation. In addition, healthy, well-structured soils can act as long-term carbon sinks by storing organic matter and supporting microbial activity that captures and retains CO_2.

6.

Noise reduction

Vegetation including the soil layer provides a physical and acoustic buffer between buildings and external noise sources.

7.

Enhance Biodiversity

Through measures such as plant choices or structures, green infrastructure create habitats for birds, insects, and pollinators.

8.

Urban Agriculture

Green roofs can support local food production and resilience, by providing space for community gardens, edible plants, and small-scale agriculture, while fostering social interaction and engagement among city residents.

© Intensive green roof system by Arup, 8 Bishopsgate, London. Joanna Karpiesiuk I Arup

C. Green building envelopes and green infrastructure

Integration in the broader design processes

Maintenance and plants selection

Green infrastructure should prioritise the use of native vegetation, which is best suited to local ecological conditions and typically requires minimal irrigation and maintenance. Where native species cannot be used due to urban constraints, climate-adapted vegetation should be selected. This approach not only supports biodiversity but also ensures these systems can endure drought periods with low water consumption, contributing to fire risk mitigation. Reducing technical infrastructure such as irrigation systems or supporting structures results in low-maintenance systems and a lower embodied carbon footprint. In addition, the selection and management of substrates should be considered as carefully as the choice of plant species to maximise environmental benefits.

Design considerations

The added weight of green infrastructure requires careful evaluation of structural capacity, particularly in building retrofits. Structural reinforcement or the use of lightweight products may be necessary to ensure safety and compliance with regulations (with associated additional cost implications).

Intensive green roofs function as rooftop gardens with diverse designs and deep soils for high water retention capacity. However, they require significant structural support, and are subject to higher maintenance, irrigation and drainage requirements, resulting in higher costs. There are a variety of extensive green roof solutions – blue-green, retention, biodiverse, solar – that offer multiple benefits and reduced costs (CAPEX/OPEX).

Green wall systems, such as vegetated mat walls, are often chosen for retrofitting projects due to their fast installation. However, they typically support a limited palette of plant species; require intensive maintenance to keep the system healthy and appealing; and higher, consistent irrigation levels.

Modular living walls are advanced systems allowing for diverse planting and precise irrigation and drainage control. However, their installation requires significant structural support and similarly associated higher costs.

Cable systems offer a flexible solution ideal for climbing plants. They are durable and low-maintenance, making them suitable for long-term applications. Yet, their effectiveness depends heavily on plant selection and local climate conditions. They require several years for plants to be established.

Planters with structural supports represent a simple and adaptable approach for green facades, particularly effective for low-rise buildings and residential projects.

Flora	Height (mm)	Weight (kg/m²)
Extensive green roof with sedum, grasses, moss etc.	50–100	10
Extensive green roof with soil, plants and small shrubs (below 0.5 m tall)	100–150	15
Intensive green roof with larger plants and small shrubs (below 1 m tall)	150–200	20
Intensive green roof with larger plants and small shrubs (below 3 m tall)	200–400	30
Intensive green roof with large plants and small trees (below 6 m tall)	400–1000	60
Intensive green roof with large plants and small trees (below 10 m tall)	over 1000	150

← **Loads of various aspects of the green roof system**

Building Smarter:

Innovations and future trends

Innovative green infrastructure

Hybrid blue-green roofs combine vegetation with water retention and storage layers, creating a dual-function system that supports both plant growth and stormwater management. Technically, these systems include a vegetation layer over a substrate, underlaid by a retention layer capable of storing rainwater for small or large rain events. This retained water acts as a passive irrigation source via capillary action. The green roof thus significantly reduces runoff during heavy rain events. Some advanced models incorporate sensors to monitor levels and optimize irrigation.

Hydroponic façades eliminate soil altogether. Instead, plants grow in inert media or directly in water-based nutrient solutions circulated through a closed-loop system. This drastically reduces system weight, making it suitable for retrofits and high-rise buildings. These façades also allow for precise climate control and easy replacement or rotation of plant species, based on seasonal or aesthetic needs (example: urban agriculture).

Finally, **bio-receptive concrete with a moss layer** introduces living surfaces that naturally host mosses and microorganisms without traditional soil or irrigation systems. Engineered with a porous texture and optimal pH levels, this precast concrete or Glassfibre Reinforced Concrete (GRC) encourages spontaneous colonization in shaded, humid environments, such as north-facing façades or underpasses. Unlike projects where vegetation struggled to adapt to orientation, it offers an inherently low-maintenance solution, requiring little to no human intervention once established.

D. Heat-Reflective and Stormwater-Permeable Surfaces

Cooler Cities, Freer Water: The Future of Urban Design

Climate adaptation brief

Heat-reflective building surfaces contribute to reduce the Urban Heat Island effect. Their application is particularly effective in hot and temperate climates where cooling demand dominates.

Cities adopting permeable pavements benefit from improved stormwater management and reduced pressure on sewage infrastructure. These systems help mitigate flood risks during heavy rainfall, support sustainable drainage strategies, and contribute to groundwater recharge.

These solutions are technically straightforward and can be seamlessly integrated into the design process with no extra effort.

These approaches could contribute directly to achieve some credits in various sustainability certifications, such as LEED, BREEAM, Green Star, Envision and SITES.

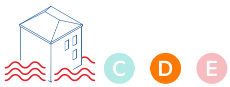
Application parameters

Unlike thermal insulation, which manages conductive heat transfer, light-coloured reflective surfaces reduce Radiative Heat Absorption, lowering surface temperatures and reducing heat transfer to surrounding air and building interiors. These surfaces minimize the absorption of short-wave solar radiation by increasing solar reflectance (albedo, Solar Reflectance Index or SRI). SRI is rated on a scale where 0 = black asphalt and 100 = standard white reflective surface, though high-performance materials can exceed 100 (e.g., SRI 110–120 in advanced coatings).

By allowing rainwater to infiltrate through their porous structure, permeable pavements reduce runoff volumes, lower flood risks, and restore more natural hydrologic cycles in urbanized areas. Thanks to their high Infiltration Rate [measured in mm/h or L/m^{2}h], these materials improve groundwater recharge.

Main hazards addressed

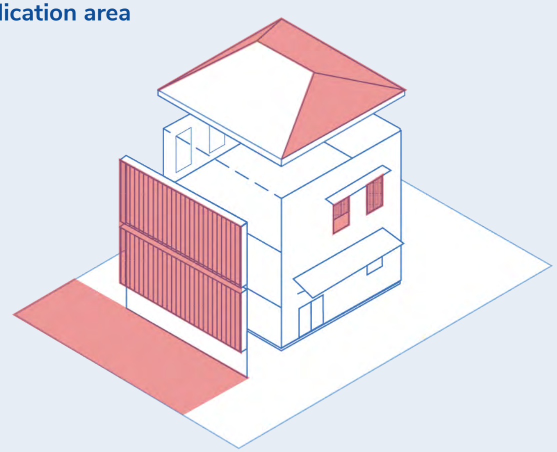
Heat waves and extreme temperatures



Flood and heavy rain

Surface Type	Reference SRI threshold values to Be Considered Reflective
Low-slope roofs	≥ 78 (according to LEED v4.1 / ENERGY STAR)
Steep-slope roofs	≥ 29
Urban pavements	≥ 29–35 (depending on use and standard)
Vertical surfaces (façades)	Not always regulated, but >30–40 can already contribute to UHI mitigation.

Application area



D1. Heat Reflective Surfaces

- Opaque façade (e.g. ceramic tiles, aluminium, concrete)
- Roof (e.g. cool roof coatings and membranes, solar panels)
- Glazing (e.g. low-e, reflective)
- Site (e.g. light-coloured concrete or pavers with high albedo, as well as membranes/ finishes with similar characteristics used in combination with bifacial solar modules to enhance performance)

D2. Water Permeable Pavements

- Site (e.g. interlocking concrete pavements)
- Roof (e.g. porous concrete slabs or gravel or crushed stone layers)

© Grupo Termotecnia – University of Seville

Cartuja Qanat

Location: Seville (Spain)

Designers: Ayuntamiento de Sevilla

Building typology: Public space

Key adaptive solutions: Heat-Reflective and Stormwater-Permeable Surfaces

Cartuja Qanat is an open-air space in Seville created through an innovative urban transformation project to address climate change and enhance public life. Its architecture integrates climate control techniques based on natural resources, along with innovative ceramic materials and concrete that reflect Andalusian tradition and culture. The project, which has involved the collaboration of several research entities, has developed ceramic solutions that promote the passive cooling of public spaces, facilitating local adaptation to rising temperatures.

In addition, it recovers and reinterprets the old Qanat system – underground cold-water channels and wind collectors – to cool the urban environment and achieve conditions of thermal comfort according to the demand of the space. In addition, it is an energy-positive intervention with a zero-water footprint. The water is naturally cooled at night and is used to reduce air and surface temperatures using radiant, convective, and evaporative cooling techniques. These bioclimatic solutions create pleasant microclimates and highlight the central objective of the project: to bring life back to the streets in a city where summers are increasingly extreme.


© LYTT Architecture

Tåsinge Plads

Location: Copenhagen (Denmark)

Designers: LYTT Architecture

Building typology: Park (Urban Space)

Key adaptive solutions: Green infrastructures

This square symbolizes Copenhagen's commitment to becoming a resilient city. It is the first square in the city specifically designed to address the challenges of climate change, particularly flooding events. Located in a densely populated neighbourhood, it incorporates green infrastructure and Sustainable Urban Drainage Systems (SUDS) to manage rainwater: during heavy rainfall, runoff is collected in three large tanks, which later release their contents into vegetated areas. In addition, this space serves as a green oasis in the heart of the city, providing a climate refuge during heatwaves.

D. Heat-Reflective and Stormwater-Permeable Surfaces

Market Overview and Regional Dynamics

The market for heat-reflective and stormwater-permeable surfaces is expanding rapidly, propelled by regulatory mandates and urban resilience imperatives that vary across regions.

In Europe, sustainability frameworks like the EU Green Deal and widespread adoption of the SuDS (Sustainable Drainage Systems) Manual have made these systems, including permeable pavements, a standard part of urban planning, especially in countries such as Germany, the Netherlands, and the UK. Cities like Paris and Barcelona further embed heat-reflective surfaces into their urban heat island mitigation strategies, supported by stringent local policies.

In India, rapid urbanization combined with intense monsoon seasons creates urgent demand for permeable surfaces that address flooding while cool materials help mitigate urban heat islands, particularly in emerging smart city developments. Cost-effectiveness and adaptability to local climatic conditions are key market factors.

The United States market is driven by scalable and economically viable solutions, with codes like the California Title 24 mandating cool roofs in select zones, and the International Green Construction Code (IgCC) setting minimum Solar Reflectance Index (SRI) values and encouraging permeable pavements. Numerous North American cities have integrated these materials into infrastructure upgrades, often supported by federal funding and sustainability programs.

	D1. Heat Reflective Surfaces	D2. Water Permeable Pavements
Europe	Adoption is growing, driven by climate targets and green building standards. Applied in urban renewal and energy-efficient construction. Example of suppliers Sika, Mapei, Thermilate Technologies, Soprema, Helios Reflect System (HRS) by Thrace Group, Alesta Cool by Axalta, Fosroc	Widely integrated into urban planning and water management systems. Supported by EU policies promoting SuDS (Sustainable Drainage Systems). Example of suppliers Cemex, Heidelberg Materials, EcoGrid Ltd, Ecoraster, Forterra, Barkman Concrete Ltd., HydroPavers, Purus Plastics, Breinco, Ecocreto, Chryso Easydrain
India	Still limited but increasing due to extreme heat in urban areas. Used in select government, commercial, and green-certified projects. Example of suppliers Cool Roofs Coating, XL Coatings, Fosroc, GCP	Primarily used in smart city developments or premium housing projects. Traditional urban areas still lack widespread adoption. Example of suppliers TuffStones, Kataline
United States	Widely used to reduce urban heat, especially in southern and sun-exposed regions. Cool roofs and reflective pavements are part of many building codes. Example of suppliers Sika, PPG Industries, The Sherwin-Williams Company, GAF, GCP	Common in cities focused on sustainable drainage and flood control. Used in sidewalks, parking lots, and green infrastructure. Example of suppliers TRUEGRID Pavers, Nicolock, Belgrad, Cemex

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D. Heat-Reflective and Stormwater-Permeable Surfaces

Co-benefits: Multifunctional surfaces for cooling and stormwater management

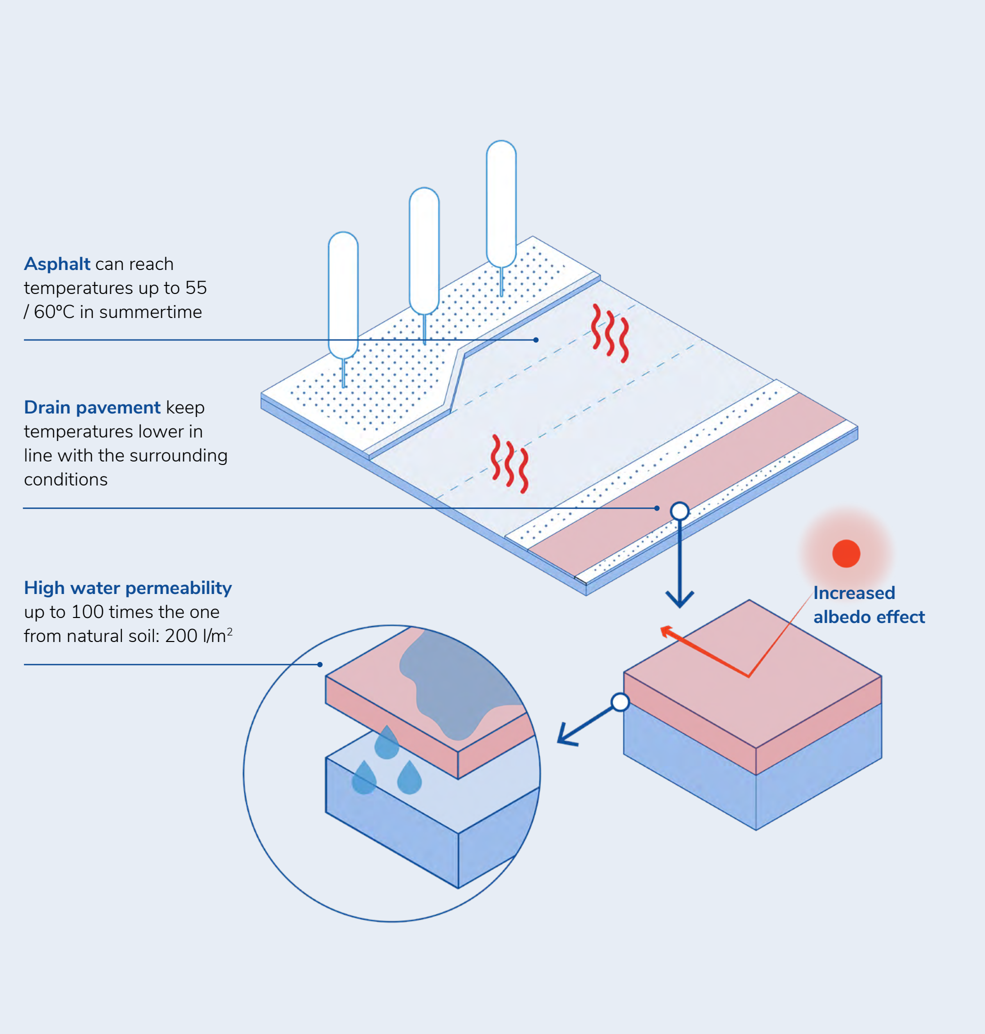
Heat-reflective and permeable surfaces deliver multiple co-benefits, simultaneously enhancing outdoor thermal comfort, lowering municipal infrastructure costs, and improving safety, while some systems provide dual performance through combined solar reflectance and stormwater management.

Beyond urban heat island effects and surface temperature reduction, heat-reflective surfaces improve outdoor thermal comfort and lower cooling loads in adjacent buildings.

Permeable pavements support efficient stormwater management, reducing the need for costly drainage infrastructure and lowering municipal costs. They also improve safety by preventing puddles, hydroplaning, and ice. In addition, installed at ambient temperature, they avoid emissions and enhance worker safety.

Some surface systems are designed to combine both solar reflectance and permeability, offering dual-performance solutions.

>> Examples of dual-performance solutions are: Mineral or polymer-based permeable coatings with embedded reflective aggregates; Interlocking permeable pavers in light tones, with high albedo and draining joints; Photocatalytic permeable pavements that cool the surface, allow infiltration, and help purify urban air.



D. Heat-Reflective and Stormwater-Permeable Surfaces

Integration in the broader design processes

Soil dependence and subsurface compatibility

The performance of permeable pavements is highly dependent on subsurface conditions. While surface materials are designed to facilitate infiltration, the underlying soil layer ultimately determines the system's drainage capacity. In areas with poorly draining soils, like compacted clay, silty substrates, or shallow bedrock, water can stagnate below the surface. This not only diminishes infiltration performance but also increases the risk of surface waterlogging, structural degradation, and localized flooding. In such contexts, additional design interventions (e.g., underdrains or engineered sub-bases) are often required to maintain function and reliability.

Winter performance and seasonal trade-offs

In temperate climates, surfaces with high solar reflectance may present seasonal inefficiencies. While these materials significantly reduce heat absorption in summer, they also reflect winter solar radiation that would otherwise contribute to passive heating and inadvertently lead to increased heating demands during colder months. The net benefit of reflective surfaces should therefore be evaluated through seasonal performance modelling, ensuring that summer cooling advantages are not offset by unintended winter energy penalties.

Maintenance and lifecycle requirements

Over time, reflective surfaces can degrade due to abrasion, oxidation, and the accumulation of dust or organic matter, diminishing their solar reflectance (aged SRI) and overall effectiveness. Similarly, permeable pavements are susceptible to clogging from sediments, vehicle debris, leaves, and other contaminants, especially in high-traffic or vegetated areas. Without proper maintenance, such as surface vacuuming, pressure washing, or sediment removal from joints and pores, infiltration and/or reflectivity capacity declines and the system's lifespan shortens. Long-term resilience depends not only on material performances but also on the implementation of predictive maintenance strategies tailored to site-specific conditions and usage patterns.

Unmanaged reflectivity

In dense urban environments, the heat reflected from highly exposed pavements or façades may be redirected toward adjacent buildings, streets, or pedestrian areas, creating localized thermal discomfort and increasing ambient temperatures, a phenomenon sometimes referred to as radiative heat trapping or localised radiative exchange, where heat is transferred to nearby surfaces. In addition, glare from overly reflective surfaces can impair visibility for pedestrians, cyclists, and drivers, and may contribute to visual discomfort or safety concerns. To avoid such outcomes, careful urban microclimate modelling and context-sensitive design are essential, ensuring that reflectivity contributes to cooling without compromising comfort or safety.

Prioritizing groundwater recharge over storage tanks

In sustainable drainage design, water storage tanks are often overused, even in areas with shallow or accessible water tables. Where infiltration is feasible, rainwater should be directed to the aquifer using infiltration trenches or soakaways, reserving storage tanks only for situations where infiltration is impractical or could compromise groundwater quality. This approach reduces infrastructure costs and supports the natural hydrological cycle.

Building Smarter:

Innovations and future trends

Advances in heat-reflective surfaces

Next-generation high-SRI materials now use **IR-reflective pigments** that deliver strong solar reflectance even in darker or coloured finishes, overcoming the trade-off between aesthetics and thermal performance. Some other **coatings reach SRI values over 100**, outperforming traditional white surfaces in both reflectance and emissivity. Photocatalytic treatments with titanium dioxide further enhance solar performance, break down airborne pollutants like NOx, and offer **self-cleaning properties** that extend surface lifespan. To endure harsh urban conditions, manufacturers are developing **UV- and abrasion-resistant coatings**, ensuring durability on high-traffic pavements.

Innovations in stormwater-permeable systems

Advanced aggregates and polymer-modified binders ensure reliable infiltration under heavy traffic and freeze-thaw cycles. More holistic are layered, performance-optimized systems that **combine surface permeability with sub-base retention or reuse layers,** buffering stormwater and enabling controlled infiltration. **Smart permeable pavements** with **IoT sensors** track temperature, clogging, and flow in real time, supporting predictive maintenance and long-term resilience in urban drainage networks.

E. Enhanced-resistance protective system

Built to Withstand the Unthinkable

Climate adaptation brief

Water-resistant building materials reduce the risk of water damage caused by heavy rains and flood, supporting structural integrity and preventing moisture-related degradation. The waterproofing strategy must be coordinated with effective vapour management to prevent moisture accumulation within the building envelope, which can lead to mold growth or material degradation over time.

Impact-resistant construction materials and systems enhance building's resilience by preventing components from being torn off or damaged by impacts (e.g. from hail or windborne debris).

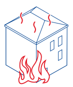
Fire resistance products are critical against bushfire and in wildfire-prone zones, protecting people, mitigating the risk of ignition and slowing the rate of fire spread to give firefighters more time to intervene.

Enhanced fastening systems use stronger and more ductile assemblies to improve connections between building envelope components, improving resistance against wind uplift and ground movement stresses.

Main hazards addressed


C D E

Flood and heavy rain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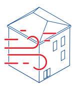
Wildfires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Extreme winds and storms

Application parameters

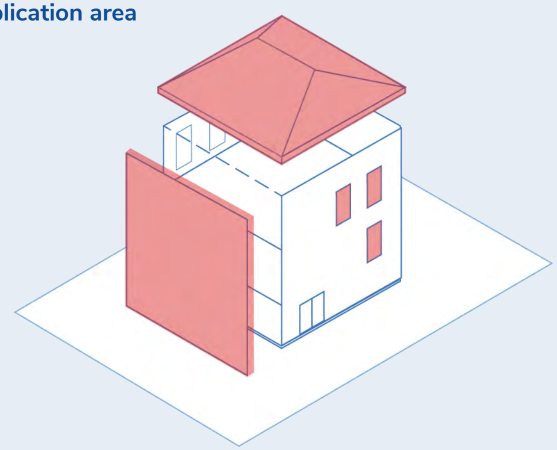
The effectiveness of water-resistant materials in building envelopes is primarily measured by their Water Penetration Resistance, typically tested through standards like ASTM E331, ASTM D5385 or EN 12155.

Impact-resistant materials are evaluated based on their ability to absorb or deflect kinetic energy from flying debris or mechanical shocks without failure. Key parameters include Impact Resistance classification, often following standards like ASTM E1996 or EN 12600, where materials must resist projectile impacts, maintaining integrity and preventing envelope breach, penetration or fragmentation.

Reaction to fire products are rated by their classification criteria, according to EN 13501-1. Most of the National Fire Regulations are requiring Class "A2-s1, d0" for façade components to ensure limited combustibility (A2), low smoke emission (s1), and no flaming droplets (d0). Class "A1" products offer the highest performance, not contributing to fire as non-combustible products. While reaction to fire is for product property, fire resistance is associated to building elements, as it concerns the ability of an entire system to maintain its performance characteristics according to EN 13501-2. It is defined by duration, typically 15 to 360 minutes, during which the building elements must maintain integrity (E), thermal insulation (I), and, where relevant, loadbearing capacity (R) under the standard temperature/time curve (ISO 834) (e.g., EI60 = 60 minutes of thermal insulation and integrity).

Improved fastening systems are assessed by their pull-out strength, load-bearing capacity, and fatigue resistance under cyclic wind loads. Tested via ASTM E330, these systems must resist uplift pressures with thresholds depending on location and code requirements.

Application area



E1. Water-Resistant Products

- Roof (e.g. waterproof membranes)
- Opaque facade (e.g. rain screen systems)

E2. Impact-Resistant Products

- Roof (e.g. metal roofing panels, high-density polycarbonate)
- Opaque façade (e.g. Fiber-reinforced concrete panels (GRC, GFRC), high-impact ceramic or porcelain panels)
- Glazing (e.g. tempered or laminated glass)

E3. Fire-Resistant Products

- Roof (e.g. clay or concrete tiles)
- Opaque façade (e.g. mineral wool insulation, concrete, bricks)
- Glazing (e.g. fire-rated laminated glass)

E4. Improved fastening systems

- Roof (e.g. hurricane ties or straps)

© FORTIFIED Home™

© Prithula Prosun Roy

FORTIFIED Home™

Location: United States

Designers: FORTIFIED Home™

Building typology: Residential

Key adaptive solutions: Enhanced-resistance protective system

The FORTIFIED construction standard is a voluntary framework created to enhance the resilience of residential and commercial buildings against extreme weather events; hurricanes, hailstorms, low-level tornados and severe thunderstorms. This standard offers a range of solutions tailored to provide varying levels of protection, depending on the building elements considered. It proposes a set of engineer and construction details which enhance the usual construction methods. Measures include roofing system requirements designed to increase uplift resistance and reduce the potential for water intrusion, others include engineered roof-to-wall connections that form a robust structure capable of withstanding high winds and storm pressures, the use of reinforced exterior sheathing designed to resist impacts from wind-borne debris or impact protection for windows and doors.

LIFT House

Location: Dhaka (Bangladesh)

Designers: Prithula Prosun Roy

Building typology: Residential

Key adaptive solutions: Enhanced-resistance protective system

The bamboo houses are two amphibious structures which are able to adapt to rising water levels. It was designed to float during floods by utilizing foundations made from either hollow ferro-cement or a bamboo frame filled with empty plastic water bottles. This approach provides a low-cost, flood-resilient housing solution, making the structures buoyant and able to rise with rising water levels, thereby reducing the risk of flood damage.

E. Enhanced-resistance protective system

Market Overview and Regional Dynamics

As climate volatility and urban densification accelerate, demand for enhanced-resistance protective systems is rising across global markets.

In Europe, regulations like the EU Construction Products Regulation (CPR) and country-specific fire safety codes are driving adoption of high-performance façades with certified resistance to fire, wind, and impact. Regulatory tightening after high-profile fire events (e.g., Grenfell tower) has led to more rigorous façade classifications, especially in countries like the UK, Germany, and France.

In India, the trend is more emergent but gaining pace. While regulatory enforcement is still evolving, the real estate and infrastructure sectors are beginning to integrate these systems in smart city projects, high-rise buildings, and transport hubs, often driven by private-sector quality standards rather than public code mandates.

In the United States, resilience-focused building codes, such as those promoted by FM (Factory Mutual) Global standards, FEMA (Federal Emergency Management Agency) guidelines, ICC (International Code Council), California Building Code, are pushing innovation in multi-hazard protective systems, especially in wildfire-prone and hurricane-affected zones. There's growing adoption of high-performance envelope assemblies that meet both insurance and code requirements, especially in coastal states. The use of wind-tested, impact-rated claddings and roofing materials is becoming standard in critical infrastructure and commercial development.

	E1. Water-Resistant Products	E2. Impact-Resistant Products	E3. Fire-Resistant Products	E4. Improved fastening systems
Europe	Highly available due to environmental regulations and varied climate. Widespread use of waterproof membranes, clay tiles, and natural slate. Example of suppliers Sika, Soprema, BMI Group, Danosa, Kemper System, Kingspan, Bauder, Moy Materials, Fosroc, Maris Polymers	Available and used mainly in hail-prone or mountainous regions. Metal, impact-rated slate, and composite tiles are gaining ground. Example of suppliers Vetrotech, Trimo, Sto, ArcelorMittal, Wienerberger, Equitone, Decra, Paroc, Gammastone, Sälzer	Tightly regulated by national and EU fire safety codes. A1-rated non-combustible products are commonly used in the building envelope. Example of suppliers Vetrotech, Isover, Rockwool, Ruukki, Kingspan, Effisus, Alpolic (Mitshubishi), Eternit, Promat, Knauf, James Hardie, Gyproc, Placo, Monokote, Armatherm, Sto, Weber, Hempel, AkzoNobel	Low to moderate adoption, more common in Nordic or alpine regions. Milder weather conditions reduce demand for advanced fixings. Example of suppliers Hilti, Fischer, SFS Group, EJOT
India	Availability is growing, driven by urban development and climate challenges. Mostly used in monsoon-prone cities and large infrastructure projects. Example of suppliers Pidilite, GCP, Maris Polymers, Fosroc, Sika	Adoption is still limited, with low awareness of impact risks. Used primarily in premium or specialized industrial projects. Example of suppliers FunderMax, FabMax, Metal Tree, Deesawala Rubber Industries	Primarily found in high-rise and commercial buildings. Less common in traditional or rural residential housing. Example of suppliers GCP, Monokote, Vetrotech, Ameetuf, Carboline, Gyproc, Everest Industries, Tata Steel Limited, Rockinsul, Owens Corning	Still limited in use, mainly in industrial or premium developments. Standard installations often lack reinforced fastening methods. Example of suppliers Hilti, Fischer
United States	Water-resistant products (e.g. bituminous membranes, synthetic coatings, and fluid-applied barriers) are widely available across the United States and common practice in both commercial and residential construction. Example of suppliers GAF, Tremco, Johns Manville, USG, Sika USA, W.R. Meadows, GCP	Widely used in coastal and hurricane-prone states, such as Florida and Texas, where building codes often require them. These materials (e.g., laminated glass, reinforced cladding) are tested to withstand extreme weather conditions. Example of suppliers Certainteed, Sto, Taktl, Guardian Glass, Anderson Windows	Fire-resistant products are increasingly used in building construction within areas prone to wildfire exposure. Example of suppliers Vetrotech, Kingspan, Monokote, CertainTeed, Tremco, Hempel, PPG Industries, USG Corporation, Owens Corning, Rockwool	Moderate to high usage, especially in wind-prone or hurricane zones. Enhanced fastening systems are often part of building code compliance. Example of suppliers Hilti, Fischer, Simpson Strong-Tie

Disclaimer: The suppliers listed in this table are provided for illustrative purposes only. The selection is informative and non-exhaustive, and the companies are not ranked or endorsed in any way. The list aims solely to represent examples of suppliers active in the regions analysed (United States, India, and Europe) and does not imply any preference, recommendation, or certification by the authors.

E. Enhanced-resistance protective system

Co-benefits: Protective Systems that Deliver Safety, Durability, and Efficiency

Enhanced-resistance protective systems boost energy efficiency and reduce insurance costs by extending building lifespan and enhancing occupant safety.

Water-resistant, fire-resistant, and impact-resistant products, along with improved fastening systems, provide multiple co-benefits beyond direct protection from extreme climate events.

The increased durability of these products and systems lowers maintenance costs and extends the building's lifespan, leading to substantial savings over its lifecycle.

From an energy perspective, improved airtightness and water resistance help maintain the effectiveness of thermal insulation, reducing heat loss and improving overall energy efficiency.

Impact-resistant products also enhance occupant safety by protecting against flying debris during storms and extreme weather, and they can reduce insurance costs by lowering the risk of damage.

State Building Authority – Administrative Headquarters

Location: Passau (Germany)

Designers: Fritsch + Tschaidse Architekten

Building typology: Government / Office

Key adaptive solutions: Fire-resistant transparent façade systems

E. Enhanced-resistance protective system

Integration in the broader design processes

The importance of detailing

Using a non-combustible material in an uncertified or poorly detailed construction does not ensure adequate fire protection. Fire resistance can only be reached through the combination of non-combustible materials and careful detailing of technological junctions to ensure proper building fire compartmentalization. Good practice includes using fire-rated seals and insulation around penetrations, installing intumescent strips at joints, and designing continuous fire barriers that prevent flame and smoke spread between compartments.

Similarly, water resistance is not solely dependent on the inherent properties of materials but critically hinges on the precision of detailing at fixings and joints, often the most vulnerable points for water ingress. Even the most advanced waterproof membranes can fail if fastening systems are improperly installed or if joint overlaps and seals do not accommodate structural movement and drainage. Effective strategies include mechanical fixings reinforced at critical load points to withstand wind and thermal stresses, combined with fully adhered waterproof membranes and properly overlapped flashing systems. The fixings themselves must incorporate adequate laps and turn-ups to create continuous barriers against water penetration. Additionally, drainage planes behind cladding and pressure-equalized rain screens help channel moisture away while allowing vapor to escape, ensuring long-term durability and preventing hidden moisture build-up.

Water and airtightness

Installing waterproof barriers without a well-defined hygrothermal strategy may backfire, potentially compromising the breathability of the building envelope, heightening the risk of interstitial condensation and mold growth.

Breathable membranes can help in preventing moisture-related maladaptation due to airtightness. These multilayer technical sheets, typically made from synthetic materials such as polypropylene or polyurethane, manage moisture dynamics within the building envelope. Their microporous structure allows water vapour to escape from inside the construction layers while blocking external liquid water, enabling drying of insulation and structural components.

Improved resistance, improved embodied carbon

Enhanced-resistance materials often come with increased cost, weight, and embodied carbon impact. As such, their use should be justified by clear performance gains and contextual risk assessments. Nonetheless, their contribution to long-term resilience can offset these initial drawbacks, as they reduce the need for frequent replacement and dismantling of damaged components over the building's lifecycle.

Building Smarter:

Innovations and future trends

Next-Generation enhanced-resistance materials

In rain screen facade systems, glass- and carbon-fibre-reinforced polymers (GFRPs, CFRPs) cladding materials combine high tensile strength and impact resistance. These systems increase resistance to flying debris, blast pressure, or seismic shock. In roofing and external areas applications, graphene-enhanced elastomers and resins are emerging as next-generation waterproofing membranes, offering potential self-healing behaviour.

Self-healing materials, are engineered to autonomously repair small cracks or damage without human intervention. Concrete may contain microcapsules filled with healing agents (bacteria or polymers) that activate when cracks form. Polymers can be embedded with reversible chemical bonds.

Bio-based fire retardants, derived from tannins, plant-based silica, or casein, are replacing conventional halogenated additives for flame inhibition while aligning with stringent environmental criteria. At the same time, **high-performance multi-layer** laminates, combining polycarbonate, EVA (ethylene-vinyl acetate), and glass, are transparent, lightweight composites engineered to absorb and dissipate kinetic energy.

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Key Fact: The report assesses building codes in 22 countries and confirms that most countries have traditionally relied on historical climate data rather than forward-looking projections, with codes typically updated in reactive cycles of 3-5 years that have proven to be inadequate for current climate conditions. World Bank Global Assessment Building Codes

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Key Fact: The roadmap identifies 13 areas across the UK most vulnerable to extreme weather hazards, with over 60% of climate-related hazards now receiving the highest urgency scores - a sharp increase from previous assessments - and modelling shows schools in London and the South East will face 10 weeks of extreme overheating risk annually under a 2°C warming scenario. UKGBC Climate Resilience Roadmap

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Key Fact: The 2024 I-Codes represent the culmination of three years of work and include numerous code changes, with enhanced flood resilience criteria, simplified wind zones, and wildfire safety measures specifically designed for climate hazards, marking a significant acceleration in climate-responsive building code development. ICC 2024 International Codes

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Key Fact: The 2025 National Building Code a substantive integration of climate change considerations in Canadian building regulations, including operational greenhouse gas emissions targets and technical requirements for existing building stock, after receiving $42.5 million in federal research funding. Canada National Building Code 2025

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Key Fact: The CSRD became mandatory in January 2025 for large companies, requiring climate adaptation disclosures and affecting approximately 50,000 companies in the European Union - more than four times the number under the previous Non-Financial Reporting Directive - with implementation driving additional investment toward climate-responsive building activities. EU Corporate Sustainability Reporting Directive

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Key Fact: California's SB 253 and SB 261 require businesses with over $1 billion and $500 million in annual revenue respectively to disclose greenhouse gas emissions and climate-related financial risks starting in 2026, with reporting deadlines remaining firm despite federal SEC climate rule withdrawal in March 2025. California Climate Disclosure Laws

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Key Fact: The EU Taxonomy's climate adaptation requirements mandate that real estate activities assess current and future climate risks and implement resilience measures, with buildings responsible for 40% of EU energy consumption and 36% of greenhouse gas emissions, requiring €275 billion annually in additional investment for building renovation across EU real estate stock. EU Taxonomy Climate Adaptation

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Key Fact: Approximately $580 billion (37%) of European commercial real estate stands in the top 10 most climate-vulnerable cities. JLL Article

63. JLL - "How climate risks are impacting real estate insurance costs" (2025)
Key Fact: US commercial premiums increased 88% over five years. JLL Article

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Key Fact: IFRS S1 and S2 climate standards became effective for annual reporting periods starting January 1, 2024, and have been adopted by 36 jurisdictions as of 2025, with the ISSB providing transition reliefs including a 'climate-first' approach allowing companies to limit disclosures to climate-related risks and opportunities in the first year. IFRS S1 S2 Climate Standards

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Key Fact: The Global Resiliency Dialogue recognises that building codes used today around the world may not provide the same level of safety and resilience for future extreme weather events as they have in the past, with participating organisations from Australia, Canada, New Zealand, and the United States collaborating to create guidelines informed by both building science and climate science. Global Resiliency Dialogue Guidelines

66. Housing, Infrastructure and Communities Canada — "Codes, Standards and Guidance for Climate Resilience" (2025)
Key Fact: Since 2016, Housing, Infrastructure and Communities Canada has collaborated with the National Research Council of Canada to create climate-informed codes that govern infrastructure development using future climate design values rather than historical climate data, with the National Model Codes reviewed and updated every five years to ensure relevance to changing climate conditions. Canada Climate Resilience Codes

67. Global Center on Adaptation – "Adapt now: a global call for leadership on climate resilience" (2019)
Key Fact: Climate adaptation investments could generate $7.1 trillion in total net benefits from 2020 to 2030. GCA Report

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Key Fact: Recent studies show that neglecting physical risks can lead to as much as 82% underestimations of Value-at-Risk for investors. Article

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Quote

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   Key Fact: Architecture responds to the human body's physiological needs such as maintaining homéothermie (37°C body temperature).

Retrofitting existing buildings is a matter of significant scale

2. European Commission "Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions: A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives" (2020)
   Key Fact: An estimated 85–95% of currently existing buildings in the European Union will remain in use by 2050. Their renovation is thus crucial for achieving significant reductions in greenhouse gas emissions and energy consumption
3. U.S. Department of Energy – "Decarbonizing the U.S. economy by 2050: A national blueprint for the buildings sector" (2024)
   Key Fact: The United States currently hosts nearly 130 million existing buildings. Between now and 2050 it is estimated that 40 million new homes and 60 billion square feet of commercial floorspace will be constructed
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   Key Fact: In the majority of developed countries, new construction only represents 1–1.5% of total building stock. Standards and policies for very high energy efficiency in the urban building sector towards reaching the 1.5°C target
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   Key Fact: Since over 90% of the buildings existing in 2025 are already constructed, enhancing the performance of these already existing structures represents a significant opportunity to achieve GHG emissions reduction objectives

Resilience and adaptation integration in the design process: strengths, opportunities and challenges

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   Key Fact: ISO 14090 and ISO 14091 provide systematic frameworks for climate risk assessment and adaptation planning
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   Key Fact: Specifies the minimum loads and load combinations that buildings and other structures must be designed to withstand, ensuring safety and consistency in structural engineering
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   Key Fact: Evaluates the performance of tall buildings during severe winds conditions providing comprehensive damage assessment
9. EN Eurocodes – "EN 1991 Eurocode 1: Actions on structures" (20)
   Key Fact: Provides design guidelines for the structural design of buildings and other civil engineering works
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    Key Fact: Scenario uncertainty presents particular challenges, especially for post-2050 projections where different SSP/RCP pathways yield substantially divergent climate futures.
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    Key Fact: Highlights limitations of probabilistic models for simultaneous heat, flood, and wind events, recommending scenario-based design frameworks that plan for a spectrum of plausible futures
12. World Bank & Inter-American Development Bank — "A Global Assessment of Building Codes: Current Status and Evolving Needs to Promote Resilient, Green, and Inclusive Buildings" (2025)
    Key Fact: While building codes are gradually updated to address new hazards—flooding, heat, and wind—their revision cycle lags behind accelerating climate risks, resulting in gaps in hazard coverage, enforcement, and adaptation integration
13. World Bank — "Unlocking Efficiency: The Global Landscape of Building Energy Regulations and Their Enforcement" (2025)
    Key Fact: Energy codes in 88 countries vary widely in stringency and enforcement
14. International Organization for Standardization (ISO) — "ISO 23932-1: Fire Safety Engineering — General Principles" (2020)
    Key Fact: Establishes performance-based fire safety objectives and criteria, enabling designers to assess building fire performance through scenario-driven analyses rather than prescriptive rules alone
15. Bentley Systems — "How Advanced Finite Element Analysis Can Prepare Buildings for the Unthinkable" (2025)
    Key Fact: Advanced finite element and multiphysics simulations enable detailed assessment of structural and envelope performance under extreme climate-induced loads, improving resilience to unforeseen events
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    Key Fact: Probabilistic hazard modelling and performance-based checks enhance traditional infrastructure design by quantifying risks from intensified wind, flood, and temperature extremes, guiding adaptive engineering solutions
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    Key Fact: Every dollar invested in code-compliant construction saves multiple dollars in future disaster losses—sometimes cited as $11 in savings for every $1 invested
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