BUILDING ENERGY CODES
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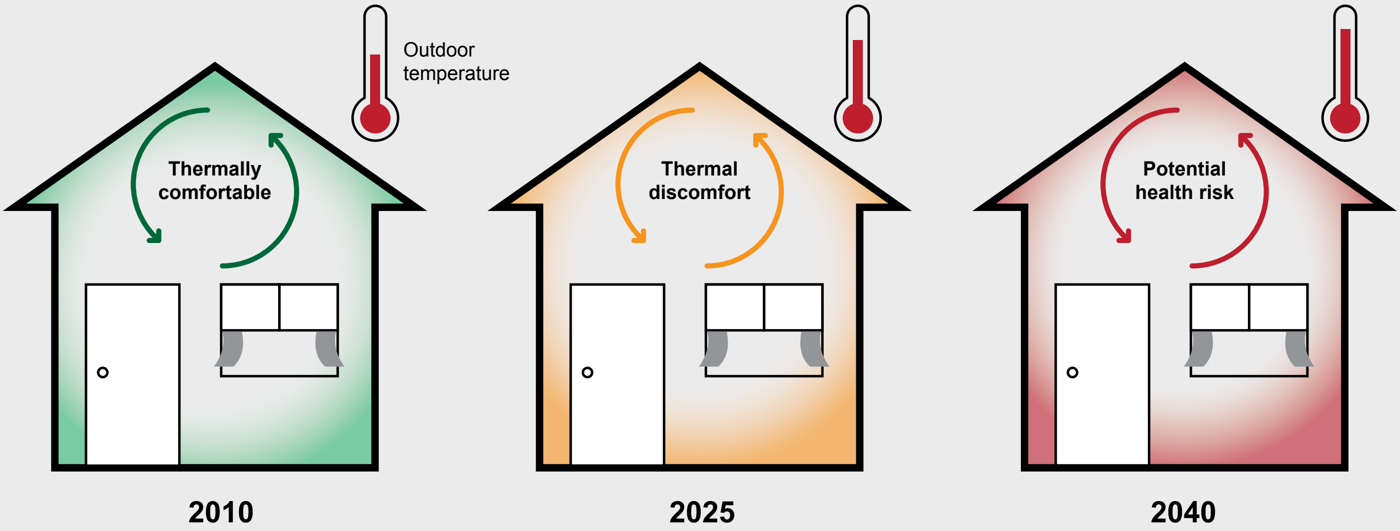
EBC
Energy in Building and
Communities Programme

Resilience Issues in Building Energy Codes

August 2023



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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019–2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:
- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:
- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019–2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting–Probability Assessment of Performance and Cost (RAP-RETRO) (*)

Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities–Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
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Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: ☼ Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings

Working Group–Energy Efficiency in Educational Buildings (*)
Working Group–Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group–Annex 36 Extension: The Energy Concept Adviser (*)
Working Group–HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group–Cities and Communities
Working Group–Building Energy Codes

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Executive Summary

Introduction

The impacts of climate change are becoming more evident with a growing incidence of extreme weather events including heat waves, massive flooding, and wildfires that are having severe impacts on human health and buildings. The built environment, and the people living, working and spending time within buildings, are particularly at risk from a variety of extreme weather events. These risks include more extreme and longer duration heatwaves, and extreme cold snaps, which can stress energy utility systems and result in possible power supply outages that prevent building heating or cooling systems from operating, and damage and pollution from increased wildfires. The risks can cause a variety of health impacts, affected by both outdoor and indoor air quality.

Because of the massive property losses from these extreme weather events, there are growing calls for new climate adaptation policies to minimize future losses, including a variety of either new or revised building codes and standards to address the increasing risks.

This report, prepared for the International Energy Agency's (IEA) Building Energy Codes Working Group (BECWG) which is part of the IEA Energy in Buildings and Communities Technical Collaboration Programme (IEA EBC), focuses on the application of building energy codes to improve the building stock's ability to provide safe indoor thermal conditions and function during extreme events.

Extreme weather and climate conditions

There are a variety of different extreme climate conditions that are affecting buildings and the people who live and work in them. Most focus on health impacts recently has been on extended heat waves, as temperatures higher than historically recorded are driving more interest in both passive and active strategies to improve building thermal comfort and passive survivability. Extended heat waves can be exacerbated by urban heat island impacts, where the density of buildings, combined with much more paved areas and a lack of vegetative cover result in an urban area having significantly higher average surface temperatures that do not drastically decrease at night because of the amount of dark absorbent surfaces like roofs, exterior walls, and paved areas that retain heat longer.

The growing incidence of large, uncontrolled wildfires (bushfires), associated with climate change, are causing serious air quality problems in surrounding areas and often in much wider geographic regions where winds blow smoky, polluted air into urban areas. The increased outdoor air pollution from wildfires is resulting in indoor air quality concerns that had not been considered in the past.

Ways to improve building resilience

There are a wide variety of different policies that governments may consider for improving the resilience of buildings. Building energy codes and regulations can address comfort, habitability, and some aspects of passive survivability but may not be as effective as addressing the broader impacts of climate change, such as infrastructure, that need to be addressed through other policies.

Building codes are established and administered first and foremost to protect people and can be especially important in areas that are prone to natural hazards, such as earthquakes, hurricanes and floods or for buildings where failure would be catastrophic, such as hospitals, schools, or other critical facilities. Building energy efficiency can be a key strategy to support climate resilience, particularly with respect to thermal comfort and passive survivability in the case of an extreme weather event.

In understanding how a building can withstand extreme weather events, including extended heat waves, design for "passive survivability" is a key strategy. Passive survivability is intended to address building habitability and the health of building occupants in the case of a variety of conditions including those caused by extreme weather events, such as power outages, extreme temperatures, drought, and other disasters, or even events such as terrorism threats.

The increased concern with changing climate conditions is also causing a review of the basic climate calculations and design temperatures used in establishing energy codes. Historically, building energy codes and regulations for addressing thermal comfort and habitability of a building have focused on the need for heat and maintaining adequate heating to meet a minimum comfort level that is considered safe. With the increase in extended heat waves and growing mortality concerns from heat risks, considering future weather data, including the extreme peak heating and cooling needs, becomes more of an issue.

There are several energy related codes that are currently in place to make buildings more livable during extreme weather events and extended power supply disruptions. These include energy code requirements that are being implemented in mandatory energy codes/regulations, voluntary, or “stretch” codes that have been developed and adopted in some leading jurisdictions, and other broader resilient design guidelines that have been enacted. The most promising, described in more detail later in the report, are:

- New York City Climate Resiliency Design Guidelines, that apply to all New York City funded capital projects, including new building and substantial renovation to buildings;
- UK Building Regulations on Overheating Mitigation, that apply to new residential buildings (both dwelling-houses and flats);
- British Columbia (Canada) Energy Step Code Design Guide Supplement S3 on Overheating and Air Quality; and,
- Stretch Energy Codes that include Resilience Requirements, in Brussels (Belgium), Massachusetts (USA), and Vancouver, British Columbia (Canada).

We are in the early days of codes or standards aimed toward building thermal resilience—there are not many mandatory thermal comfort or passive survivability provisions in mandatory energy codes. Assessing how these codes and policies work in reality will take time and data—and will be complex. There will also need to be regard to the potential for unintended consequences, where in trying to address one problem, we don’t inadvertently create another.

There is much that the industry has not yet figured out about resilience and building energy codes. First and foremost, few jurisdictions have tried. Beyond that, we are still trying to figure out what measures may be most impactful. Much research will be needed in the coming years to understand how we learn from climate induced events, and how can we speed our growing understanding in light of the various uncertainties in climate, technology, engineering, and policy.

1. Introduction

All around the world, the impacts of climate change are becoming more evident with a growing incidence of extreme weather events including heat waves, massive flooding, and wildfires that are having severe impacts on human health and buildings. Record temperatures in 2021 resulted in a new high of 3.7 billion more person-days of heatwave exposure among people older than 65 years and 626 million more person-days affecting children younger than one year, compared with the annual average for the 1986 to 2005 baseline (Romanello et. al. 2022).

There are also growing concerns about building safety due to increasingly frequent and extreme weather events. The International Finance Corporation has estimated that over 7,000 weather-related natural hazard events between 2000 and 2019 have affected over 4 billion people and claimed nearly 1.25 million lives, causing US$2.97 trillion in economic losses, a very significant increase from the previous 19-year period running from 1980–1999 (IFC 2022). The economic losses associated with natural hazard weather events over the last decade increased by almost US$1 trillion from the previous decade (Buchholz 2021).

Because of the massive property losses from these extreme weather events, there are growing calls for new climate adaptation policies to minimize future losses, including a variety of either new or revised building codes and standards to address the increasing risks. The Global Alliance for Buildings and Construction (GlobalABC), organized by the UN Environment Programme (UNEP), has issued a Call to Action on Buildings and Climate Change Adaptation articulating the consequences of climate change to the building and property sector and providing a number of recommendations to governments and other stakeholders to address the challenge (GABC 2021).

The GlobalABC notes that the significant increase in hazards from extreme weather events requires the building sector to pursue climate adaptation and mitigation measures simultaneously. For example, while cooling systems are required to keep buildings comfortable and safe, they must also be designed to reduce their emissions and be fully integrated into efficient building design. The GlobalABC also found that submersion from flooding and heatwaves are the two biggest risks facing the building sector.

This report, prepared for the International Energy Agency's (IEA) Building Energy Codes Working Group (BECWG) which is part of the IEA Energy in Buildings and Communities Technical Collaboration Programme (IEA EBC), focuses on the application of building energy codes to improve the building stock's ability to provide safe indoor thermal conditions and function during extreme events. It reviews the relationship of building energy codes to other building resilience policies and strategies, such as other building/life safety codes, community planning, zoning or other land use regulation to discourage rebuilding in areas most prone to climate disasters, and other resilience planning strategies. The report provides an overview of how different jurisdictions address resilience issues through building energy codes in countries that are part of the IEA EBC Building Energy Codes Working Group.

This report was prepared in early 2023, but as it is being finalized in summer 2023, much of the northern hemisphere including North America, Europe and Asia are suffering from extreme heat along with massive uncontrolled wildfires, adding to the urgency of solutions to keep buildings and their occupants safe.

1.1 Definitions of Resilience

Before going more deeply into potential resilience (sometimes called resiliency) strategies, it is important to understand the definition of the term as applied to buildings and public safety.[1]

At the broadest level, the United Nations, as part of its Common Guidance on Helping Build Resilient Societies, defines resilience as "the ability of individuals, households, communities, cities, institutions, systems and societies to prevent, resist, absorb, adapt, respond and recover positively, efficiently and effectively when faced with a wide range of risks, while maintaining an acceptable level of functioning without compromising long-term prospects for sustainable development, peace and security, human rights and well-being for all" (UN 2020).

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[1] While this report focuses on resilience issues driven by climate change and extreme weather events, some stakeholders also refer to energy resilience in the context of energy security. The current situation in Europe, where there have been major disruptions in energy supply due to the war in Ukraine, and major gas supply disruptions, has resulted in major energy supply resilience concerns. The uncertainty of energy supply, and potential for major energy shortages that might result in rationing of energy and other policies, has led to European policy makers proactively planning to create a systemically more resilient energy supply than had been taken for granted in recent years, including significant energy efficiency and conservation programs at the European Union (EU), and EU Member State and local jurisdictional levels.

The International Code Council (ICC) has developed a broad, but more concise, definition of resilience as "the capacity of society, organizations, infrastructure, and the natural environment, individually and collectively, to effectively prepare and plan for, absorb, recover from, and successfully adapt to adverse events" (Sollod & Colker 2022).

The Global Building Resilience Guidelines[2] developed by the Global Resiliency Dialogue, focused on climate-related risks, and comprising national building code writing bodies and research organizations from the United States, Canada, Australia and New Zealand, further refines the definition for climate resilience in buildings as "the ability of a building and its component parts to withstand current and future climatic conditions (including wildfires/bushfires, extreme wind, extreme precipitation and extreme temperature), to minimize the loss of functionality and recovery while sustaining damage proportionate to the intensity of the events experienced, and preserving the intended level of performance at the time of construction over the proposed design life of the building" (Global Resiliency Dialogue 2022).

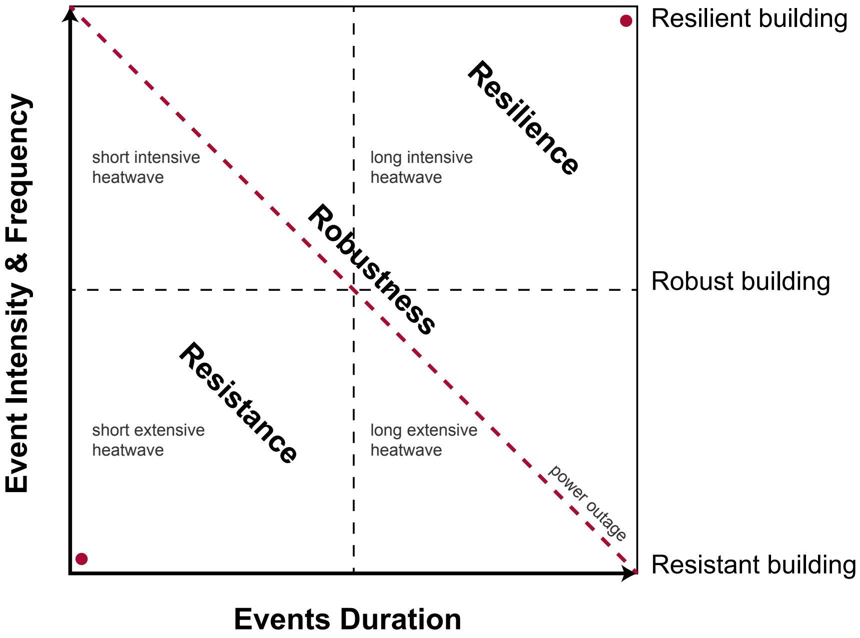
The US Department of Energy more specifically defines Energy Resilience as "the ability to operate building energy services, such as heating, cooling, ventilation, critical plug loads, and shelter, during and in response to a major disruption, and can be defined by two central functions: Passive Survivability and Grid Resilience:

- Passive Survivability: The ability to maintain safe indoor conditions in the event of extended energy outage or loss of energy supply. In practice, passive survivability enables safe indoor thermal conditions, relying on building design measures that require no energy. As a measure of a building's thermal performance, passive survivability offers an integrated assessment of both energy efficiency and resilience.

- Grid Resilience: Building energy technologies that provide efficiency and grid flexibility services. These technologies can provide grid services during peak demand periods. Demand load reductions alleviate energy supply and grid constraints, thereby decreasing the risk of power system failures." (US DOE 2023).

A different IEA EBC Technical Collaboration project, Annex 80: Resilient Cooling of Buildings, is looking to understand and promote resilient cooling applications in buildings, with an emphasis on developing supportive technology profiles and design guidelines for practical building design.[3] The Annex 80 project team identified the components of a resilient building in the face of extreme climate events, as shown in Figure 1.

Figure 1. Components of a resilient building definition (Attia et. al. 2021)



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[2] Guidelines are available at: https://www.iccsafe.org/wp-content/uploads/22-21730_COMM_72922_Global_Resilience_Guidelines_FINAL_2.pdf

[3] More information about IEA EBC Annex 80 on Resilient Cooling can be found at https://annex80.iea-ebc.org.

The definitions of resilience presented in this section are somewhat overlapping and relate to one another. The similarities, differences and overlapping characteristics of these definitions are captured in Table 1. For this report, we consider a resilient building to be one that has the ability to provide safe indoor thermal conditions and function during extreme events.

1.2 Potential Health and Morbidity Impacts

The built environment, and the people living, working and spending time within buildings, are particularly at risk from a variety of extreme weather events. These risks include more extreme and longer duration heatwaves, and extreme cold snaps, both of which can stress energy utility systems and result in possible power supply outages that prevent building heating or cooling systems from operating, and damage and pollution from increased wildfires. The risks can cause a variety of health impacts, affected by both outdoor and indoor air quality. All of these weather events impact building thermal comfort and indoor air quality, and building energy codes can improve the capacity of buildings to endure such extreme events.

Most focus on health impacts recently has been on extended heat waves, as temperatures higher than historically recorded are driving more interest in both passive and active strategies to improve building thermal comfort and passive survivability. Extended heat waves can be exacerbated by urban heat island impacts, where the density of buildings, combined with much more paved areas and a lack of vegetative cover result in an urban area having significantly higher average surface temperatures that do not drastically decrease at night because of the amount of dark absorbent surfaces like roofs, exterior walls, and paved areas that retain heat longer.

The Lancet Countdown on health and climate change, an international collaboration that independently monitors the health consequences of a changing climate, has identified several key indicators related to health and heat, particularly: exposure to warming; exposure of vulnerable populations to heatwaves; heat and physical activity; and heat-related mortality. The research shows a dramatic increase in the exposure of vulnerable populations to heatwaves, especially impacting children under the age of one and adults older than 65. They also found that over the past ten years, high heat posed at least a moderate heat stress risk during light outdoor physical activity during a much larger fraction of the year than 20 years ago (Romanello et. al. 2022).

With the summer of 2022 being the hottest season on record in Europe, researchers attempted to quantify heat-related mortality burden. Using the Eurostat mortality database, they found that there were more than 61,000 heat-related deaths in Europe between 30 May and 4 September 2022 (Ballester 2023).

However, there are also major risks to health during extended winter cold snaps that result in power utility outages and heating system failures. This was clearly demonstrated in February 2021 during Storm Uri in the State of Texas when 69% of residents lost electricity for an average of 42 hours, while almost half—49%—lost access to running water for an average of more than two days; at least 246 deaths in Texas have been directly attributed to the storm (University of Houston 2021). Similar examples of mortality caused by power outages have been documented during high heat events, particularly with elder care facilities where HVAC systems are typically not included in the “essential loads” connected into the backup power systems required for life support and building functionality.

1.3 Need for Resilience in Buildings/ Risks from Insufficient Mitigation

There is growing concern about risks to people and property from extreme weather events. The risk to buildings is broad, including direct damage, indirect damage from

Table 1. Summary of Main Resilience Definitions

Term	Definition
Resilience	The ability of individuals, households, communities, cities, institutions, systems and societies, individually and collectively, to effectively prepare and plan for, absorb, recover from, and successfully adapt to extreme events
Building Resilience	The ability of a building and its component parts to withstand current and future climatic conditions, while minimizing a loss of functionality and recovery time
Energy Resilience	The ability to operate building energy services, such as heating, cooling, ventilation, critical plug loads, and shelter, during and in response to a major disruption

cold, heat or water, or to other nearby infrastructure. The potential financial impacts of these weather events are being quantified by insurers, and there is growing discussion about limiting rebuilding in the most vulnerable risky areas following destruction of property from climate induced disasters. In 2023, two of the US State of California's four largest property insurers, State Farm and Allstate, stopped selling or accepting new home insurance policies due to growing risks (Los Angeles Times 2023).

The Insurance Council of Australia, in their second annual Insurance Catastrophe Resilience Report, used insurer data and insights to review extreme weather events and advocate for changes to reduce the impacts on insured property of future events (ICA 2022). Among the Insurance Council recommendations are:

- Improving home energy efficiency which will reduce energy use and makes homes more livable, while reducing emissions that contribute to worsening extreme weather events;
- Establishing a common national database for enhanced mapping, modelling and projections for climate change and extreme weather events to avoid or limit development in highly exposed areas;
- State planning and design policies that ensure new homes are built to mitigate and adapt to the risk of climate change; and,
- Increased Australian Government investment in extreme weather resilience measures broader than energy.

Following severe flooding in various parts of Australia in the second half of 2022, and massive wildfires around the North American West Coast, and other recent extreme weather events, it has become clear that some areas severely impacted will need to be abandoned, and not rebuilt as certain properties become uninsurable. Some experts have raised the concept of "managed retreat" from the most vulnerable areas susceptible to climate impacts, though that can be a very loaded topic. While not directly linked to building energy codes, it will be critical to have a more widespread debate about the costs of climate adaptation and building resilience policies, to develop a more balanced set of requirements for rebuilding following disasters as opposed to condemning certain properties with the recognition that they are not safe (The Economist 2022).

Development occurring in flood-prone areas throughout North America and other regions, as well as uninhabitable areas due to more frequent and intense wildfires, have caught the attention of the insurance industry. Swiss Re, a leading wholesale provider of reinsurance, insurance, and other insurance-based forms of risk transfer, estimates that the world stands to lose around 10% of total economic value from climate change by mid-century (Swiss Re 2021).

An extreme weather event that disrupts the operation of power plants or other critical infrastructure could result in cascading infrastructure failures, as evidenced with the February 2023 Cyclone Gabrielle event in New Zealand that flooded a major regional electric power substation, resulting in power outages to significant populations in the country (The Guardian 2023).

Widespread power outages caused by failures of certain key electrical transmission or distribution system components have occurred in many parts of the world over the past twenty years. A recent study of critical infrastructure failures during extreme weather events in the U.S. found that the intensity and duration of recent compound heat wave and grid failure events could expose between 68 and 100% of the urban population to an elevated risk of heat exhaustion and/or heat stroke (Stone et. al. 2021).

There is also a separate but related compounding issue of multiple climate impacts affecting grids at once. For example, the potential of drought limiting available hydroelectric power capacity, high temperatures increasing demand, and then a storm or wildfire that knocks out additional generation or transmission capacity could have cascading impacts which have dire consequences for people in buildings.

1.4 Range of Resilience Strategies for Buildings

More resilient buildings can help in the above situation in two ways. First, they can reduce stress on the grid. Second, they can make power outages more survivable.

While this report focuses on the intersection of building energy codes and resilience, and specifically on application of energy codes to improve the ability of buildings to provide a minimum, survivable level of thermal comfort and function during extreme events, there are a broad range of different strategies, and resulting government regulatory processes, that can help address resilience in buildings. Some strategies are aimed more toward new construction, while other leading jurisdictions have studied potential regulations to impact the much larger existing building stock.

One example showing the range of different resilience strategies that can be applied to existing buildings is captured in Table 2, developed as part of a study for the City of Boston, Massachusetts (in the US), that examined different strategies and policy options that affect resilience in existing buildings.

As shown in the table, there are many resilience strategies impacting buildings that are beyond the scope of building codes. These include the General Actions and Site strategies which are generally addressed in regional and local planning and zoning regulations or other government policies, or features of human behavior which are best

Table 2. Resilience Strategies for Existing Buildings (Linnean Solutions et. al. 2013)

Category	Action
General Actions	Assess Vulnerability and Risk
	Create Places of Refuge
Site	Build for Higher Rainflow
	Create Cool Ground Surfaces
	Floodproof Building Site
	Floodproof Industrial Buildings
	Use Hard Infrastructure to Prevent Flooding
	Use Hazard Resilient Landscape Design
	Protect Entrances from Snow and Ice
	Provide Shade
	Reduce Vulnerability to Wind Damage
	Use Soft/Green Infrastructure to Prevent Flooding
	Stabilize Slopes Susceptible to Erosion, Landslide, Fire
	Fire
Building Structure	Enhance Structural Elements for Extreme Loads
Building Enclosure	Use Cool Roofing
	Enhance Building Insulation
	Increase Resistance to High Winds
	Manage Heat Gain
Building Systems	Resilient Back-up Power and Systems
	Resilient Heating, Cooling and Ventilation Systems
	Resilient Water Systems During Outages
	Extend Emergency Lighting and Services
Building Operations	Have Emergency Communications Plans
	Protect Records and Inventory
	Secure Interior Environment
	Train Building/Facility Teams for Resilience Upgrades
People	Educate Households
	Partner with Local Community Organizations to Enhance Resilience
	Locate Vulnerable Populations
	Plan for Tenant Needs

addressed through education. The types of strategies that can be addressed through building energy codes are described in the following sections of this report.

1.5 The Role of Other Building Regulations

Finally, other building regulations (including building life safety codes) can also play an important role in supporting building resilience. The World Bank, through its Global Facility for Disaster Reduction and Recovery, has noted that as the scale, frequency, and severity of natural hazards continue to rise, so will future expected losses in the built environment (World Bank 2016). With these potential losses in mind, the World Bank has proposed a Program of Building Regulation for Resilience, which would include four separate but linked, components, including country level building code development, with dedicated local implementation, as shown in Figure 2.

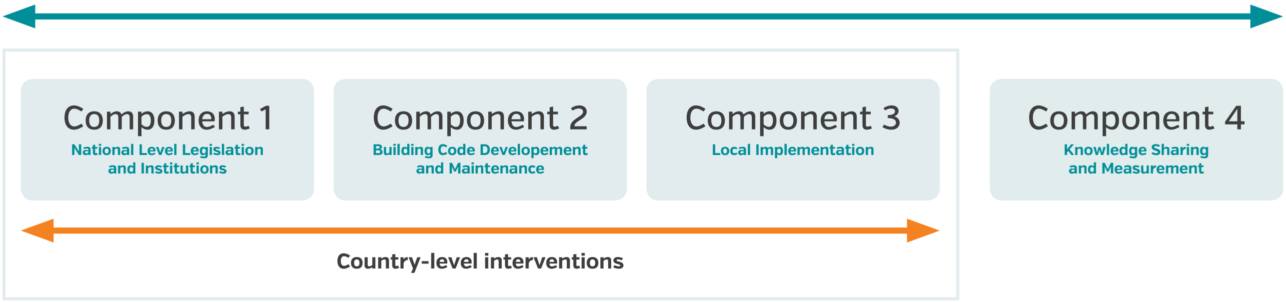
The International Code Council (ICC), the leading global source of model codes and standards and building safety solutions, has partnered in the Global Resiliency Dialogue, with the goal of identifying solutions to help address the global challenge posed by the impact of increasingly frequent and extreme weather events and hazard risks (including heatwaves) on building occupants and buildings. The Global Resiliency Dialogue has two overarching objectives:

- To understand and disseminate the latest in climate science and building practices to help inform the ongoing development of building codes that improve the resilience of buildings and structures around the world.
- To enhance the utility of current building codes to respond proportionately to rapidly changing and predicted extreme weather events such as flooding, severe storms, cyclones/hurricanes, wildfires/bushfires and heatwaves.

The Global Resiliency Dialogue has developed the Global Building Resilience Guidelines, a set of Guidelines for Resilient Buildings to Extreme Weather (Global Resiliency Dialogue 2022). The Global Resilience Guidelines identify 15 critical principles for the development of building codes that advance the resilience of buildings to climate-related hazards, as summarized in Box 1 (next page).

Other building regulations and life safety codes have an important role to place in improving the resilience of buildings and can play a complementary role to building energy codes.

Figure 2. Proposed Building Regulation for Resilience Program (World Bank 2016)



Box 1. Principles that provide a basis for advancing building resilience through building codes (Global Resiliency Dialogue 2022)

1. Urgency

The need to respond to the associated impacts of climate change and extreme weather events on buildings and building occupants is more urgent than ever.

2. Clarity of objectives

Building resilience requires attention to the changing climatic conditions buildings will face over their lifecycle and impacts on their expected operation following an extreme weather event. The importance of building codes focusing on occupant health and safety remains.

3. Robust climate science

Building code development will benefit from an evidence base that utilizes official climate forecasts in the local jurisdiction or models based on peer-reviewed scientific research and ideally provide a demonstration of various future state possibilities.

4. Risk clarity

Risk informed thinking and decision making is important in providing support for design decisions to balance cost, energy performance, greenhouse gas emissions and resilience, where changing risks can be balanced against certainty of performance for building development and maintenance.

5. Forward-looking

A baseline assessment of current technical construction standards, where they exist, enables a comparison to be made with modelling and scenarios for future climate to help determine if they remain adequate or if new ones need to be developed.

6. Durability

Understanding building design life is important not only to assist in determining minimum necessary technical construction standards, but to also calibrate the technical design requirements. This will help improve the resilience of buildings with a benchmark of durability that avoids unnecessarily harsh requirements and therefore costs.

7. Holistic approach

Building codes can contribute to improving building resilience as part of a broad suite of regulatory and non-regulatory measures. In some cases this will be interdependent and take account of multi-hazard weather related events.

8. Affordability

Building codes and standards consider, where possible, a regulatory principle of setting minimum requirements necessary to achieve the level of desired performance, while doing so cost effectively. This should also achieve the objective of improved building resilience, throughout the design life of a building, to the effects of weather-related natural hazard events under a range of future scenarios.

9. Existing buildings

Identify strategies to encourage existing building owners to bring their buildings up to a higher standard of resilience for the types of future weatherrelated natural hazards they may experience based on their location and climate projections.

10. Building maintenance

Encourage property owners to engage in the need for planned periodic and specified maintenance of their buildings and promote essential resilience features embedded within buildings to ensure their ongoing performance.

11. Compliance

Effective regulatory systems will incorporate appropriate resources to properly enforce the building codes and standards, as well as promote an ethic of compliance.

12. Implementation

Complement any regulatory measures to improve compliance and support technical solutions with a wide range of education and practitioner capacity building tools.

13. Monitor and evaluate

Routinely monitor the need to maintain the currency of building codes and standards in response to updated climate science and projections.

14. Engagement

Employ a clear and uncomplicated communication strategy that embraces and simplifies risk-based information; uses a common, credible and consistent set of evidence; and caters to the many and varied views of those with an interest in this subject.

15. Emissions reduction

Building code development can make an important contribution to mitigating the causes of climate change with subsequent long-term benefits for building resilience.

2. Issues for Building Energy Codes and Regulations

Building codes are established and administered first and foremost to protect people and can be especially important in areas that are prone to natural hazards, such as earthquakes, hurricanes and floods or for buildings where failure would be catastrophic, such as hospitals, schools, or other critical facilities. Building energy efficiency can be a key strategy to support climate resilience, particularly with respect to thermal comfort and passive survivability in the case of an extreme weather event.

Building energy efficiency, as regulated through energy codes and regulations, can provide multiple resilience benefits, as summarized in Table 3.

Energy codes provide minimum requirements for healthy, comfortable and efficient thermal conditions in a building, and can include requirements that provide safe, healthier indoor thermal environments during extreme heat or cold events, or prolonged power supply outages.

2.1 Resilience Risks to Building Thermal Comfort

There are a variety of new risks from climate change where building energy codes may be able to help with longer term resilience, particularly in the area of thermal comfort. As noted earlier, research has documented mortality risk from both extended high and low temperature events, so a building with a better thermal envelope should be better able to withstand more extreme weather conditions, including when power outages might limit the operation of building heating or cooling systems.

As mentioned earlier, among the risks to building thermal

Table 3. Resilience Benefits of Energy Efficiency (Ribiero et. al., 2015)

Benefit type	Energy efficiency outcome	Resilience benefit
Emergency response and recovery	Reduced electric demand	Increased reliability during times of stress on electric system and increased ability to respond to system emergencies
	Backup power supply from combined heat and power (CHP) and microgrids	Ability to maintain energy supply during emergency or disruption
	Efficient buildings that maintain temperatures	Residents can shelter in place as long as buildings' structural integrity is maintained
	Multiple modes of transportation and efficient vehicles	Several travel options that can be used during evacuations and disruptions
Social and economic	Local economic resources may stay in the community	Stronger local economy that is less susceptible to hazards and disruptions
	Reduced exposure to energy price volatility	Economy is better positioned to manage energy price increases, and households and businesses are better able to plan for future
	Reduced spending on energy	Ability to spend income on other needs, increasing disposable income (especially important for low-income families)
	Improved indoor air quality and emission of fewer local pollutants	Fewer public health stressors
Climate mitigation and adaptation	Reduced greenhouse gas emissions from power sector	Mitigation of climate change
	Cost-effective efficiency investments	More leeway to maximize investment in resilient redundancy measures, including adaptation measures

comfort, building overheating has received the most recent attention due to increasing global surface temperatures attributed to climate change, though extreme cold snaps are occurring more frequently in some regions. Unexpected cold snaps have caused stresses on electricity and gas delivery systems in some regions, resulting in extended power outages leaving buildings without heat, as experienced in 2021 in Texas.

There are also increasing risks from a growing number of longer and more intense wildfires, resulting in significant levels of outdoor air pollution across large regions, driving a need for filtration and more air conditioning to improve indoor air quality when people are forced indoors for extended periods due to wildfire smoke.

All of these risks can be addressed through modern building energy codes, though heat waves and concerns about building overheating have received the most attention to date in codes.

2.2 Heat Waves and Building Overheating

The growing incidence of longer and more extreme heat waves, is leading to more heat-related deaths and increased awareness of the need for better thermal comfort conditions to protect the health of occupants within buildings. The World Meteorological Organization has forecast that there is a 98% chance that one of the years between 2023 and 2027 will exceed the current record from 2016 for the hottest year on record, and that the average temperature in this time period will almost certainly be the warmest ever recorded for a five-year period (WMO 2023).

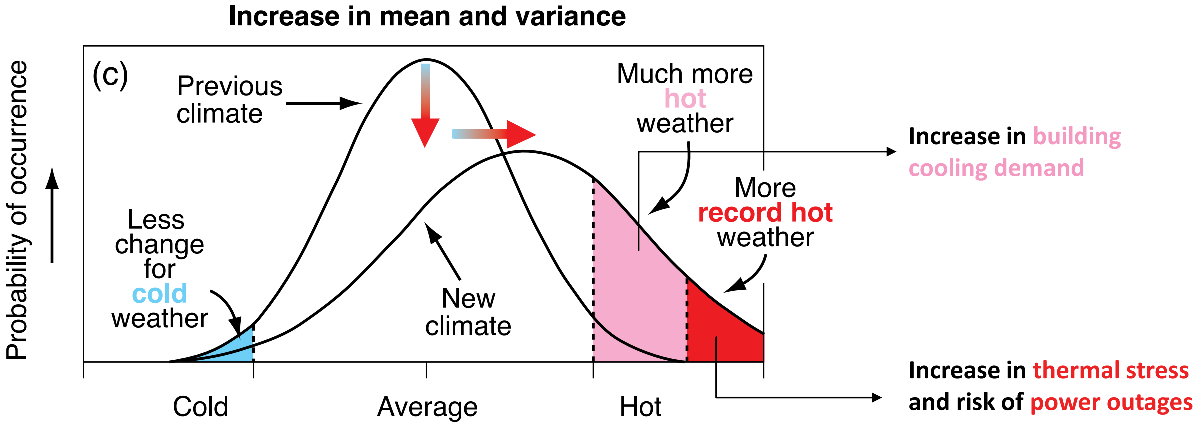
Building overheating is different from thermal discomfort, a mature topic in air-conditioned and naturally ventilated buildings. Overheating expresses the cumulative effect over continuous days of environmental conditions related to both the comfort and the health of the occupants (Laouadi et. al. 2022).

While the issue of building overheating and need for better thermal comfort for occupants has become an issue globally, an increase in the intensity and duration of heatwaves in northern regions and much of Europe where air-conditioning has traditionally not been widely used, have raised societal awareness of the need for better understanding of overheating buildings. This has been a significant issue in the UK, leading to policy makers driving new code activity to tackle overheating through passive cooling measures.

In response, the Chartered Institution of Building Services Engineers (CIBSE) has published a range of resources on building overheating, first issuing Technical Memorandum CIBSE TM52: 2013, The limits of thermal comfort: avoiding overheating in European buildings (CIBSE 2013). TM52 acknowledged that in the effort to reduce energy consumption, much research has been directed toward methods for improving winter heating energy efficiency, but this can lead to lightweight, highly insulated buildings that can easily overheat in the summer. TM52 recognized that “overheating” is not precisely defined or understood, but implies that building occupants feel uncomfortably hot and that the discomfort is caused by the indoor environment.

In 2017, CIBSE published a Technical Memorandum (CIBSE TM59), the Design methodology for the assessment of overheating risk in homes (CIBSE 2017). TM59 acknowledged that overheating risk was considered a complex issue and not adequately assessed by building regulations, and it would be wrong to assume that a home that complies

Figure 3. Future weather and heatwaves (Salvati 2022)



with building regulations designed to focus on energy conservation would also address concerns about overheating. The Technical Memorandum was intended to provide a standardized methodology to assess risk.

Concerns about overheating and public safety have continued to grow with more heat waves and increasing deaths. In 2021, the Climate Change Committee, the UK's statutory advisory committee to the UK government on climate change, noted that "the government's failure to address the challenge of adapting the built environment to climate change will condemn thousands of people to death in overheated buildings, … and urged the government to revise Building Regulations to tackle overheating in new and refurbished homes by introducing passive cooling measures" (CIBSE 2021).

The Climate Change Committee's Call to Action led to a formal study, Addressing Overheating Risk in Existing UK Homes, that quantified the overheating risk in the UK domestic housing stock and the potential costs and benefits of policy measures to decrease the risk (Arup 2022). This has resulted in the UK being the first country to formally issue building regulations to minimize building overheating (see Section 3.2).

The European Air Infiltration and Ventilation Centre's (AIVC's) Venticool platform has hosted several webinars on the IEA EBC Annex 80 Resilient Cooling work, including one on future weather data and heatwaves.[1] The overheating risk from the combination of both many more instances of hotter weather, and more record hot weather, is shown in Figure 3, from the AIVC/Annex 80 webinar.

2.3 Urban Heat Islands

Urban and suburban areas often experience elevated air temperatures compared with nearby outlying rural areas. Buildings, roads and other infrastructure replace open land and vegetation, absorbing more heat and raising the temperature in more densely populated areas.

The annual mean near-ground air temperature of a city with a million or more people can be 1 to 3°C (1.8 to 5.4°F) warmer than its surroundings, and on a clear calm night the temperature difference can be as much as 12°C (22°F). These elevated temperatures can be caused by the sun heating exposed surfaces, like roofs and pavement, to a level much hotter than the prevailing air temperature (US EPA 2008).

A wide variety of strategies can reduce urban heat island impacts, including "cool roofs" such as high-reflectance white roofs or planted green roofs, and other strategies such as use of trees and landscaping to reduce heat gain and provide shading to avoid absorption of heat by buildings, sidewalks, roads and other infrastructure. Many useful references on these strategies have been catalogued through a study on Cool Roofs Mitigation Potential in Australian buildings, including a helpful compilation of Cool Roof resources (UNSW 2023), as well as a summary of resources on urban greening as a solution to urban heat islands (Clean Air and Urban Landscapes Hub 2023).

2.4 Resilient Cooling

With the rapid increase in the use of air conditioning in buildings, there is a need to develop, assess and communicate solutions of resilient cooling and overheating mitigation. As noted earlier, the IEA EBC Annex 80 Resilient Cooling of Buildings program has convened a wide range of international researchers and experts to address these topics and study resilient cooling solutions. Annex 80, which includes participants from 36 institutions in 16 countries (including the Americas, Europe, Asia and Australia), has a group working specifically on future weather data and heatwaves.

The Annex 80 work has developed a conceptual model of a resilient cooling system centered on people, the socio-cultural-technical contexts they inhabit, and the risks posed by the temperature hazard. The review enabled the research team to characterize the nature of the temperature hazard, the functionality characteristics of a resilient cooling system, and key elements of the four subsystems: people, buildings, cooling technologies and energy infrastructure (Miller et. al. 2021).

The ability of a building to provide resilient cooling, when compared with other design typologies attempting to address cooling (robust or resistant buildings, as described earlier in Section 2.1), is demonstrated in Figure 4 (next page) that shows how building thermal performance might respond when subjected to different heat stresses and other future climate disruptions affecting mechanical cooling availability.

2.5 Passive Survivability

In understanding how a building can withstand extreme weather events, including extended heat waves, design for

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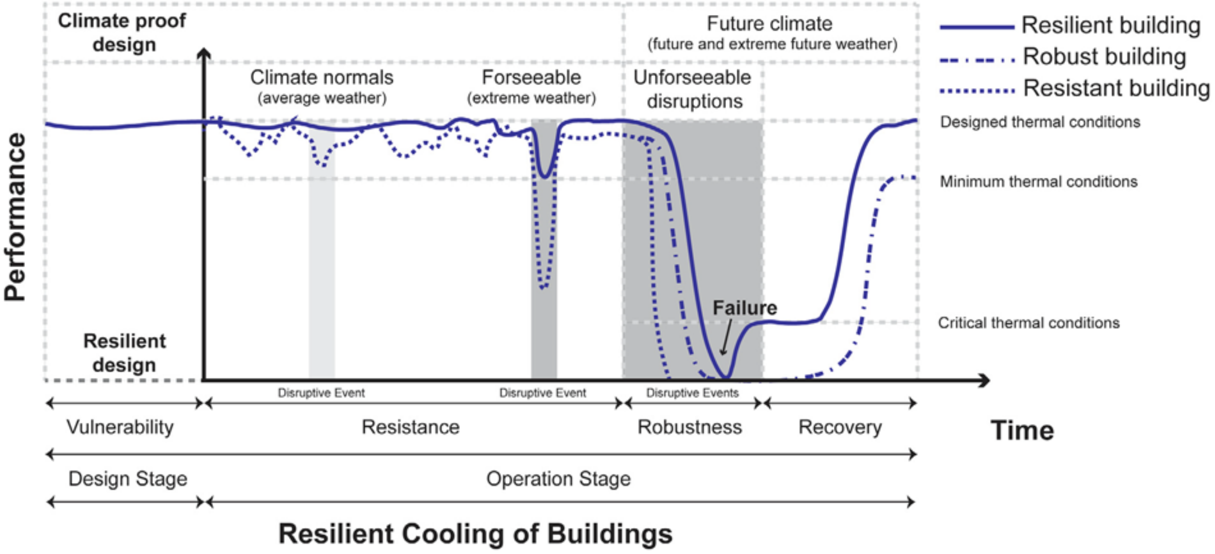
[1] See full list of AIVC webinars at: https://www.aivc.org/events/webinars. The presentation and videos from the AIVC/Annex 80 webinar on future weather data and heatwaves are posted at: https://www.aivc.org/event/31-may-2022-webinar-future-weather-data-and-heatwaves.

Figure 4. Differentiating climate resilient cooling in buildings from robust or resistant buildings (Attia et. al. 2021)



"passive survivability" is a key strategy. Passive survivability refers to a building's ability to maintain critical life-support conditions in the event of extended loss of power, heating fuel, or water (Wilson 2005). This concept, first developed following the wake of Hurricane Katrina in the Southern US in 2005, encourages designers to incorporate ways for a building to continue safely sheltering inhabitants for an extended period of time during and after a disaster situation, whether a storm that causes a power outage, a drought that limits water supply, or any other potential event.

Passive survivability is intended to address building habitability and the health of building occupants in the case of a variety of conditions including those caused by extreme weather events, such as power outages, extreme temperatures, drought, and other disasters, or even events such as terrorism threats. Passive survivability building design strategies include a very carefully considered building envelope, along with passive solar design to provide heat, heat avoidance strategies such as shading to minimize heat gain into the building, natural ventilation to provide some level of cooling and fresh air, and daylighting to minimize the need for artificial lighting. Other more active features that can extend survivability are backup power generation, either through backup generators with adequate fuel or on-site renewable systems with energy storage, and emergency water supply systems like rainwater harvesting systems.

The Passive House standards developed by the Passive House Institute[2] and Passive House Institute US (PHIUS)[3] include many passive design strategies that provide significant passive survivability benefits.

2.6 Indoor Air Quality Issues from Wildfires

The growing incidence of large, uncontrolled wildfires (bushfires), associated with climate change, are causing serious air quality problems in surrounding areas and often in much wider geographic regions where winds blow smoky, polluted air into urban areas. Wildfires in many parts of the world in 2023 have impacted areas not previously affected. The increased outdoor air pollution from wildfires is resulting in indoor air quality concerns that had not been considered in the past.

With widescale smoke and other pollutants circulating outside during a wildfire, public health agencies are providing guidance about using air filters and other air conditioning/specialized filtering systems to protect building occupants' health during severe smoke situations. They recommend that residents stay inside buildings with windows and doors closed, potentially requiring more mechanical air conditioning when natural ventilation was otherwise adequate to keep the indoor space comfortable. This is likely to increase energy use in buildings from additional air conditioning needs, or use of new filter systems consuming energy, some of which may be regulated through energy codes.

Guidance on protecting citizens from wildfire smoke has been developed by the California (US) and New South

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[2] See https://passivehouse.com/02_informations/01_whatisapassivehouse/01_whatisapassivehouse.htm

[3] See https://www.phius.org

Wales (Australia) governments (California Air Resources Board 2023, and New South Wales Health 2023).

2.7 Including Future Weather Data/ Design Conditions in Energy Codes

The increased concern with changing climate conditions is also causing a review of the basic climate calculations and design temperatures used in establishing energy codes. Historically, building energy codes and regulations for addressing thermal comfort and habitability of a building have focused on the need for heat and maintaining adequate heating to meet a minimum comfort level that is considered safe. With the increase in extended heat waves and growing mortality concerns from heat risks, considering future weather data, including the extreme peak heating and cooling needs, becomes more of an issue.

Most building energy regulations, and the related thermal comfort standards that define acceptable comfort and habitability, rely on "Typical Meteorological Year (TMY)" weather data, sometimes called Test Reference Year, that is based on historic average low and high temperatures in any given region or climate zone. Significant research goes into these weather data sets, and the "design conditions" for any given city or climate are used for sizing the peak heating and/or cooling equipment design capacity. Generally, TMY weather data does not address extreme weather events, but is based on longer term average trends.

The Global Resiliency Dialogue partners surveyed relevant government agencies about how climate-related data is used in building codes, and particularly the frequency of updating weather data in codes. They found that climate data is generally only updated on a 10-year cycle on average, so as weather becomes more extreme from year to year, the underlying data simply does not accurately reflect the risk to a building from the growing number of extreme weather-related events (Global Resiliency Dialogue 2021).

Some stakeholders have noted that cold temperatures and heating design conditions drive the need for insulation and better building envelopes, and that as temperatures rise it could become less cost effective to have stringent insulation requirements and other energy efficiency measures. There may be a need in the future to differentiate weather files used for survivability versus those used for calculating energy cost savings in different climate zones.

Some leading jurisdictions are looking to provide forward looking weather data in response to climate change, particularly regarding peak summer heat temperatures for future proofing air conditioning system sizing. The Climate Resiliency Design Guidelines developed in New York City present current and projected future extreme heat events and cooling system design criteria, with the historic trend (1971–2000) having 2 heat waves per year with 18 days at or above 32.2°C (90°F), with cooling system design criteria for 1% dry bulb temperature[4] at 32.8°C (91°F), and 1,149 cooling degree days (base 18°C / 65°F). Buildings that are expected to be in use in the 2050's should plan for 7 heat waves per year with 57 days at or above 32.2°C (90°F), and corresponding dry bulb design temperature of 37°C (98°F), and 2,149 cooling degree days (base 18°C / 65°F), an 87% increase in cooling degree days.

The IEA Annex 80 Resilient Cooling of Buildings work program is working to assemble future heatwave weather files for representative cities around the world, including at least one city for each climate zones in the ASHRAE[5] climate zone classification, and cities with high population and expected population growth (Salvati 2022).

2.8 Metrics of Resilience for Energy Codes

The US Department of Energy (DOE) has recognized the need to better understand the relationship between energy efficiency and resilience, including the need for standardized metrics, establishment of evaluation methods, and impact assessment for both residential and commercial buildings. DOE commissioned three national research laboratories led by Pacific Northwest National Laboratory (PNNL) to develop a standardized methodology to quantitatively assess how energy efficiency measures affect building thermal resilience (Franconi et. al. 2023).

The PNNL report proposes a measurement of passive survivability using the Standard Effective Temperature (SET) as the metric. SET is a comfort indicator that considers indoor dry-bulb temperature, relative humidity, mean radiant temperature, and air velocity, as well as the activity rate and clothing levels of occupants. SET thresholds for livability are generally considered to be between 12° and 30°C (54° and 86°F), with a cumulative value of SET degrees falling outside the SET thresholds (expressed as SET degree hours) that exceed 216 over a seven-day period indicating uninhabitable conditions (Franconi et. al. 2023).

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[4] The 1% dry bulb temperature represents the ambient air temperature and is used in the design of HVAC systems.

[5] ASHRAE is the American Society of Heating, Refrigerating and Air-Conditioning Engineers.

3. Relevant Resilience Provisions in Leading Jurisdictions

This section describes some of the relevant codes that are currently in place to make buildings more livable during extreme weather events and extended power supply disruptions. These include energy code requirements that are being implemented in mandatory energy codes/ regulations, voluntary, or "stretch" codes that have been developed and adopted in some leading jurisdictions, and other broader resilient design guidelines that have been enacted.

IEA EBC Annex 80 has catalogued 37 different potential policy recommendations, identified by policy mechanisms such as regulation, information, incentives, R&D, and standards, that jurisdictions might consider for addressing resilient cooling of buildings that have been compiled into a summary report, including an online matrix that can be sorted to filter the recommendations by category, policy mechanism, and disruption(s) mitigated (Levinson et. al. 2023).

We present in this section relevant requirements that are enacted in jurisdictions that are leading on resilience efforts, categorized by the level of ambition and comprehensiveness.

3.1 New York City Resilience Guidelines

Superstorm Sandy struck New York City and surrounding communities in October 2012. Extreme sustained winds along with an intense storm surge destroyed roughly 300 homes, left hundreds of thousands without power, damaged critical infrastructure and left many vulnerable with limited access to food, drinking water, healthcare, and other critical services.

In response to Superstorm Sandy, New York City strengthened a number of resilience provisions in its building codes, but also set out to develop Climate Resiliency Guidelines to establish a consistent approach for applying forward-looking climate change data across the City's capital plan. In September 2016, New York City formed a Resilient Design Working Group composed of 15 City agencies.

The resulting Climate Resiliency Design Guidelines were first issued in April 2017, and following field testing of the Guidelines with actual City government facility projects, has been updated since then. The most recent version is the Climate Resiliency Design Guidelines version 4.0 published in September 2020. The Design Guidelines address multiple hazards: extreme heat, extreme rainfall, tidal inundation considering sea level rise, and coastal storms. Adherence to the Guidelines is required for all types of New York City funded capital projects, including new build and substantial improvements to buildings (residential, commercial and institutional), infrastructure and landscapes (NYC 2020).

The Guidelines distinguish between short and long-lived capital facilities and components, with different recommended climate change projections based on the expected life of the capital asset, as shown in Table 4.

The Guidelines also provide projected design criteria for cooling equipment sizing, and projected number of and intensity of extreme heat events, based on the end of the expected life of the facility HVAC systems, as shown in Table 5.

3.2 Building Regulations for Overheating in England

With the concerns noted in Section 3.2 (Heat Waves and Building Over Heating) about building overheating in the UK, the UK government initially added a new Requirement O1: Overheating Mitigation, to the Building Regulations of 2010. Approved Document O took effect in June 2022 and applies to new residential buildings (both dwellinghouses and flats) in England (HM Government 2022).

Approved Document O of the Building Regulations presents two methods for compliance: a simplified method, intended to be quicker and easier to use, but that is more prescriptive, and another more flexible route that requires dynamic thermal modeling. The focus of the simplified method is on glazing areas, and the "free areas" when the windows are open, the availability of cross-ventilation, and the building's location within England. Mechanical cooling is discouraged, with a clear preference stated for passive design measures, though there is no firm requirement restricting air-conditioning systems or equipment.

The dynamic modeling option in Approved Document O generally follows CIBSE TM59, though with some changes including:

– Internal blinds are not to be included in the model;

Table 4. Facilities and components and associated climate change projections (from NYC 2020)

Climate change projections (time period covered)	Examples of building, infrastructure, landscape, and components grouped by typical useful life	
2020s (through to 2039)	Temporary or rapidly replaced components and finishings	– Interim and deployable flood protection measures – Asphalt pavement, pavers, and other ROW finishings – Green infrastructure – Street furniture – Temporary building structures – Storage facilities – Developing technology components (e.g., telecommunications equipment, batteries, solar photovoltatics, fuel cells)
2050s (2040–2069)	Facility improvements, and components on a regular replacement cycle	– Electrical, HVAC, and mechanical components – Most building retrofits (substantial improvements) – Concrete paving – Infrastructural mechanical components (e.g., compressors, lifts, pumps) – Outdoor recreational facilities – At-site energy equipment (e.g., fuel tanks, conduit, emergency generators) – Stormwater detention systems
2080s (2070–2099)	Long-lived buildings and infrastructure	– Most buildings (e.g., public, office, residential) – Piers, wharfs, and bulkheads – Plazas – Retaining walls – Culverts – On-site energy generation/co-generation plants
2100+	Assets that cannot be relocated	– Major infrastructure (e.g., tunnels, bridges, wastewater treatment plants) – Monumental buildings – Road reconstruction – Subgrade sewer infrastructure (e.g., sewers, catch basins, outfalls)

- The rate at which windows are assumed to be open is explicitly set, depending on the outdoor temperature; and,

- Depending on outdoor temperature, bedroom windows are required to be left fully open all night.

With Approved Document O just coming into force in 2022, there is not yet much evidence about how well new homes built to meet the new requirements will perform relative to other homes.

3.3 British Columbia Energy Step Code

The Energy Step Code in the Canadian province of British Columbia (BC) is one of the compliance paths allowed for design and construction in BC, and establishes both total energy use intensity, and thermal energy use intensity limits for certain building occupancy types (BC 2018). In 2017, the province of BC established the Energy Step Code Council to support the successful implementation of the BC Energy Step Code and the market transition to net-zero energy ready buildings (Energy Step Code 2023).

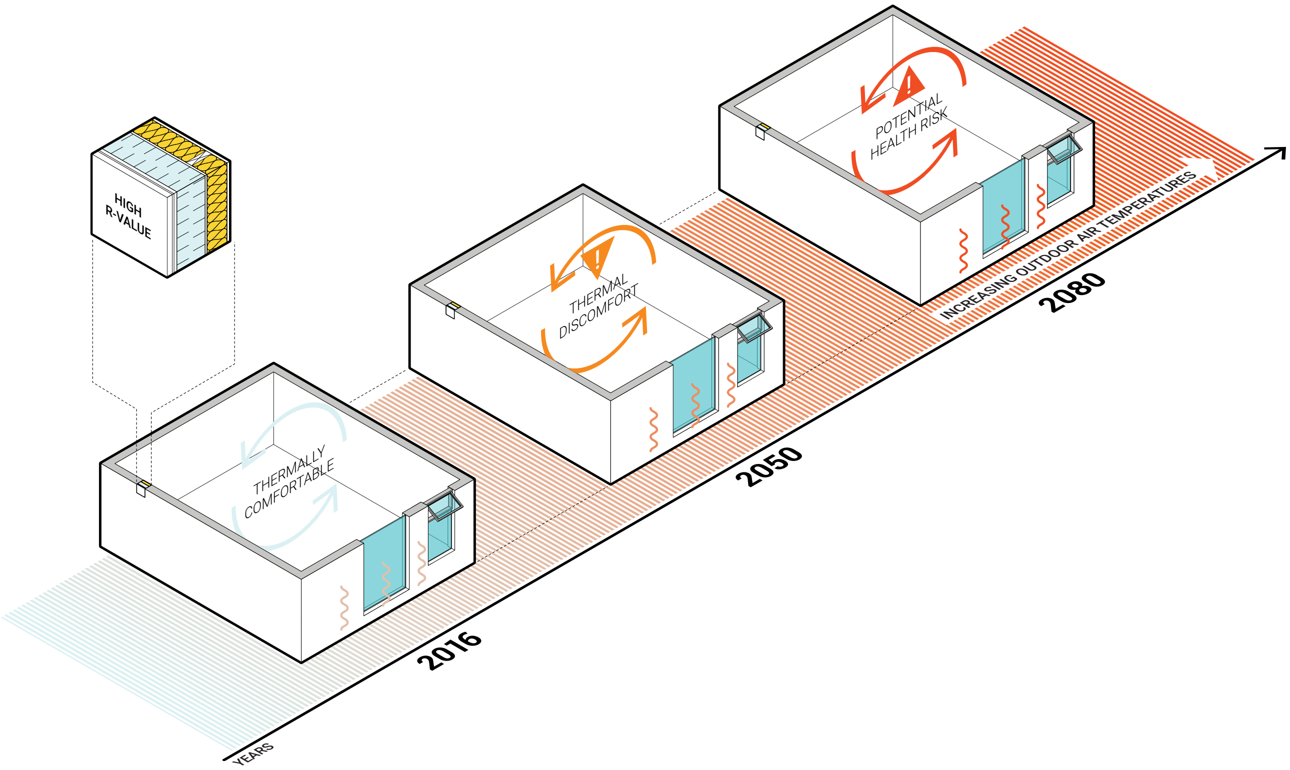
The BC Energy Step Code references a number of Design Guide Supplements prepared through the Energy Step Code Council and involved stakeholders, including BC Energy Step Code Design Guide Supplement S3 on Overheating and Air Quality, intended to provide building industry market actors with an accessible source of information on the key means of addressing issues of overheating and indoor air quality (BC Energy Step Code 2019).

Table 5. Current and projected extreme heat events and design criteria (adapted from NYC 2020)

	Extreme Heat Events				Design Criteria		
Select period that aligns with end of useful life	# of heat waves per year	# of days at or above 32oC (90oF)	Average annual temperature		1% Dry Bulb Temperature		Cooling Degree Days Base 32°C (90°F)
			°C	°F	°C	°F	
Historic Trend (1971–2000)	2	18	12.2	54	32.8	91	1,149
2020s (through to 2039)	4	33	14	57.2	—	—	—
2050s (2040–2069)	7	57	15.9	60.6	36.7	98	2,149
2080s (2070–2099)	9	87	17.9	64.3	—	—	—

Note: Due to HVAC system typical useful life of around 25 years, only design criteria projections for the 2050s are shown. Projections for the 2020s are not shown because it is anticipated that enough of a safety margin is employed already in current systems to withstand the temperature rise expected through the 2020s. The NPCC is developing projections of 1% Wet Bulb temperatures, which are expected to increase.This design criteria will be added in a later version of the Guidelines.

Figure 5. Comfort today can be discomfort tomorrow (From British Columbia Energy Step Code 2019.)



Design Guide Supplement S3 includes information on Risk and Resilience in Building Design; Modeling for a Future Climate; and Key Design Strategies for these issues. The information in the Design Guide is intended to future proof buildings, with the understanding that what is considered comfort in a building currently may not remain so in the future, as shown in Figure 5.

3.4 Stretch Energy Codes That Include Resilience Requirements

In many parts of the world, national building codes include energy efficiency provisions that are adopted as the building regulatory requirements by the national government or states and provinces in countries with federal systems of government. While these codes become the minimum prescriptive or performance requirements for buildings, local governments in some cases, have the option to adopt a more stringent energy code, and in recent years, the development of model "stretch" or "reach" codes for adoption by leading jurisdictions has been a way to demonstrate more ambitious requirements in advance of being able to reach national consensus about the stretch code. Differences in governance arrangements between central and federated systems allow greater capacity for stretch codes. Development and implementation of stretch energy codes are also a mechanism for jurisdictions to advance energy efficiency in their building stock and move forward on their ambitious climate goals at a different pace than others in the state or region.

Passive House Standards (referenced in Section 2.5, Passive Survivability) establish rigorous thermal envelope requirements intended to significantly reduce energy use, and conceptually will deliver a level of passive survivability for occupants in those buildings due to dramatically lower mechanical heating and cooling demand.

These stretch codes have been adopted in several regions, in many cases including Passive House building shell requirements:

- Brussels, Belgium—in 2011 the Brussels Regional Authority passed the Passive House Law, paving the way to requiring the Passive House standard for all new construction since 2015. This has resulted in a rapid increase in passive house buildings and a significant reduction in carbon emissions (Building Innovations Database 2022).

- Massachusetts, USA—the State of Massachusetts has developed a Stretch Energy Code and Municipal Opt-in Specialized Code.[1] The stretch code emphasizes energy performance, while the Specialized Code ensures new construction is built consistent with MA's greenhouse gas limits. These stretch energy codes provide flexibility to jurisdictions and surpass the proposed base code modeled on the 2021 International Energy Conservation Code. The State has also allowed a Passive House Institute US (PHIUS) certification as an alternative compliance path since 2012.

- Vancouver, British Columbia, Canada—in 2016 the Vancouver City Council adopted a Zero Emissions New Building Plan that defined a path for new construction delivering better envelopes, lower heating energy needs and reduction of fossil fuel usage. The city established energy efficiency regulations for the city code in 2019, and in 2021 approved requirements to reduce GHG emissions from new multi-family and commercial buildings, establishing a maximum net heat loss of 30 kWh/m^2, consistent with Passive House standards (MEEA 2020).

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[1] See https://www.mass.gov/info-details/building-energy-code for more information.

4. Broader Framework and Policies to Drive Resilience in Buildings

Many policy measures that address resilience go beyond building energy codes and related regulations. The Global Building Resilience Guidelines, prepared by the Global Resiliency Dialogue, catalogs a number of examples of successful incorporation of building resilience measures into local policies (Global Resiliency Dialogue 2022). Among the types of measures noted in the Global Building Resilience Guidelines (GBRG) are:

- Extreme wind events: In the US, extreme wind events typically take the form of hurricanes (cyclones), tornados and severe storms (including derechos). The GBRG presents case studies of stringent wind standards being adopted into the residential building code in the City of Moore, Oklahoma, as well as New York City adopting provisions in the building code.

- Managing multi-hazard risks from flooding in New Zealand: Following a series of earthquakes in 2010 and 2011, a series of multi-hazard events took place including land damage, floods and increased extreme rainfall. These events led to changes to the New Zealand Building Code requiring a hazard mapping exercise as part of hazard mapping identification process, with specific rules that limit development in higher risk areas.

To address the risks of flooding and wildfires that are increasing due to climate change, some local zoning and planning regulations are being considered or adopted which prohibit construction (or reconstruction) in vulnerable areas. These types of policies get into a range of different social policy and equity concerns that are being widely debated, as data related to property risks and very high costs of reconstruction following these types of extreme weather events become more clear. Policymakers will need to balance the various policy priorities and tensions as they work to develop policy solutions and regulations to ensure that buildings can withstand these increased climate-driven risks.

4.1 Framework for Resilience Planning

As the Canadian government has been examining the benefits of low-carbon renovations and new energy codes for military housing through the Canadian Forces Housing Agency, Natural Resources Canada organized a workshop on this topic where there was a discussion about climate resilience for buildings, including a framework, presented by Lepage (2021), for different actions to reduce risk, as shown in Figure 6 below. This framework proposes a process for balancing hazard mitigation and climate change mitigation, to increase resilience and reduce vulnerability in buildings.

4.2 Voluntary Building Resilience Rating Tools

While well beyond just resilience in buildings for improved thermal comfort and passive survivability, two voluntary building resilience rating tools have been developed for use by different groups of stakeholders.

RELi is a voluntary building and community resilient design rating system that takes a holistic approach to resilient design. RELi allows various building sector stakeholders and planners to assess and plan for all of the acute hazards that buildings and communities can face during unplanned events, to prepare to mitigate against these hazards and to design and construct buildings to maintain critical life-saving services in the event of extended loss of power, heating fuel or water.[1]

The International Finance Corporation, the private sector lending arm of the World Bank, has developed the Building Resilience Index, a web-based hazard mapping and resilience assessment framework for the building sector. It is designed to facilitate access to location-specific natural hazard information, provide resilience measures to mitigate applicable risks, and improve transparency for disclosing a building's resilience information between sector stakeholders (IFC 2022). The Building Resilience Index is organized around four major hazard categories:

- Wind, including storms such as cyclones, typhoons and hurricanes, tornados and other downbursts;

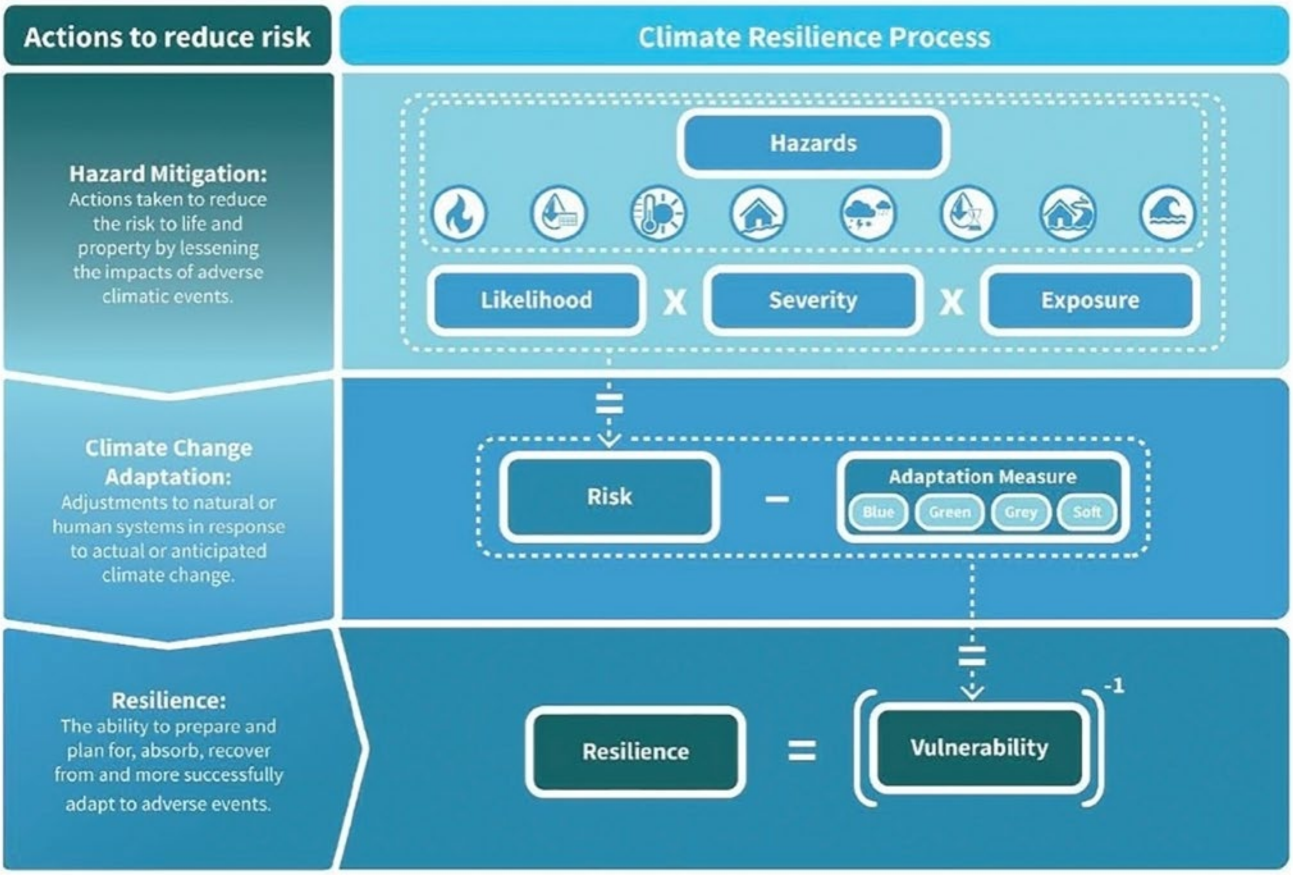
- Water, including various causes of floods, storm surges and tsunamis;

- Fire, from wildfires or other local fire sources; and,

- Geo-seismic, including earthquakes, volcanos, landslides and others.

[1] More information about RELi can be found at https://www.gbci.org/reli and https://www.gbci.org/us-green-building-council-announces-reli-system-be-managed-and-operated-institute-market .

Figure 6. Framework for Climate Resilience Process Planning (Lepage 2021)



5. Conclusions

Growing concerns about the impacts of extended and more severe heat waves, along with other extreme weather events driven by climate change upon occupants of buildings, are driving increased interest in how buildings can become more resilient, and the potential role of building energy codes and related regulations to deliver this.

There are a wide variety of different policies that governments may consider for improving the resilience of buildings. Building energy codes and regulations can address comfort, habitability, and some aspects of passive survivability and can be one part of a comprehensive package that includes complementary land use policies such as building orientation, density and green canopies.

While the New York City Climate Resiliency Design Guidelines are very comprehensive, they only apply to projects funded by the City government and have not yet been expanded to apply to the broader private building stock. The Building Regulations for Overheating in England and British Columbia Energy Step Code should be watched closely, and as implementation proceeds may be able to be replicated in other jurisdictions' codes.

We are in the early days of codes or resilience standards aimed toward building thermal resilience—there are not many mandatory thermal comfort or passive survivability provisions in mandatory energy codes. Assessing how these codes and policies work in reality will take time and data—and will be complex. There will also need to be regard to the potential for unintended consequences, where in trying to address one problem, we don't inadvertently create another.

There is much that the industry has not yet figured out about resilience and building energy codes. First and foremost, few jurisdictions have tried. Beyond that, we are still trying to figure out what measures may be most impactful. Much research will be needed in the coming years to understand how we learn from climate induced events, and how can we speed our growing understanding in light of the various uncertainties in climate, technology, engineering, and policy.

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