Resilient Buildings for a Round Planet: Mitigating Operational Risks with Adaptation Strategies

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ABSTRACT

This literature review provides an overview of opportunities for building owners and operators to understand 1) the risks associated with climate change and 2) the strategies for avoiding and/or mitigating those risks in existing building stock. Climate change will impact intensity and frequency of temperature, precipitation, coastal erosion, air quality, pests and wildfires. The associated risks to building owners and operators will depend on whether they are located in a hotter/drier or colder/wetter climate. We reviewed current research to date and compiled resiliency strategies as applicable to existing buildings. The strategies are sorted into the following categories: Energy Systems, Water Systems, Envelope, Equipment, Site/Landscaping, Materials, and Operations. We have focused our research on North America, but many of the strategies can be implemented outside of that geographic area.

Introduction

There are many resources available for building owners and operators to reduce or mitigate the environmental impact of their buildings, most often in the form of energy efficiency. This has been a very successful strategy for addressing climate change because the business case is clear: saving energy is saving money. However, even if these efforts are successful, the effects of climate change are already underway and will continue for decades to come (IPCC 2007b). For this reason, ensuring that buildings can withstand extreme or unpredictable weather is key to increasing long term value and reducing exposure to risk.

In addition, while climate mitigation strategies are essential, the effects are rarely felt at the community level. Adaptation and resiliency have a more direct visibility and impact on the local community because the strategies are by nature designed for that specific geographic location and can have benefits beyond operational cost savings.

According to the Whole Building Design Guide, resiliency refers to "the capacity of a building to continue to function and operate under extreme conditions, such as (but not limited to) extreme temperatures, sea level rise, natural disasters, etc." Adaptability refers to "the capacity of a building to be used for multiple uses and in multiple ways over the life of the building. For example, designing a building with movable walls/partitions allow for different users to change the space." (WBDG 2013)

A clear business case is emerging for adaptation and resiliency as the concepts gain momentum in both the private and public sectors. Recent studies show that the costs of adaptation will range from $75 billion to $100 billion per year between 2010 and 2050 (WBG 2010). Already natural disasters have cost the US economy over $100 billion (Smith 2013). In California alone, 62% of real estate assets are at risk from extreme weather events, sea level rise, and wildfires with a projected annual price tag of up to $3.9 billion (Kahrl 2008). According to a study conducted by the National Institute for Building Science, however, for every dollar spent on disaster preparedness, four dollars are saved on future recovery costs (MMC 2005).

Future Extreme Climate Conditions in the US

The term "global warming" is a misnomer for climate change. As the Intergovernmental Panel on Climate Change (IPCC) has noted in the Fourth Assessment Report issued on climate change impacts, we should not only anticipate warmer temperatures, but also more extreme weather events including flooding, storm surges, droughts, and heat waves (IPCC 2007b). For this reason, resiliency strategies should be prioritized differently based on geographic location.

Of all the climate change impacts we face there are two that are perhaps most immediately felt across the US: change in temperature and precipitation. The maps below illustrate these projected changes given a worst case emissions scenario.

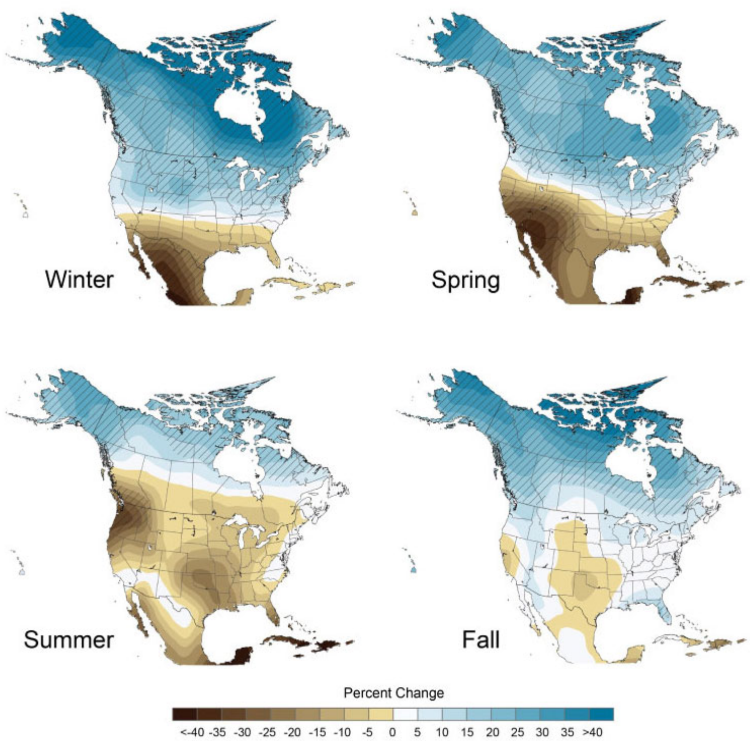

Figure 1. Projected future changes in precipitation relative to the recent past as simulated by 15 climate models. The simulations are for later this century, under a higher emissions scenario. For example, in the spring, climate models agree that northern areas are likely to get wetter and southern areas drier. *Source:* US GCRP 2009.

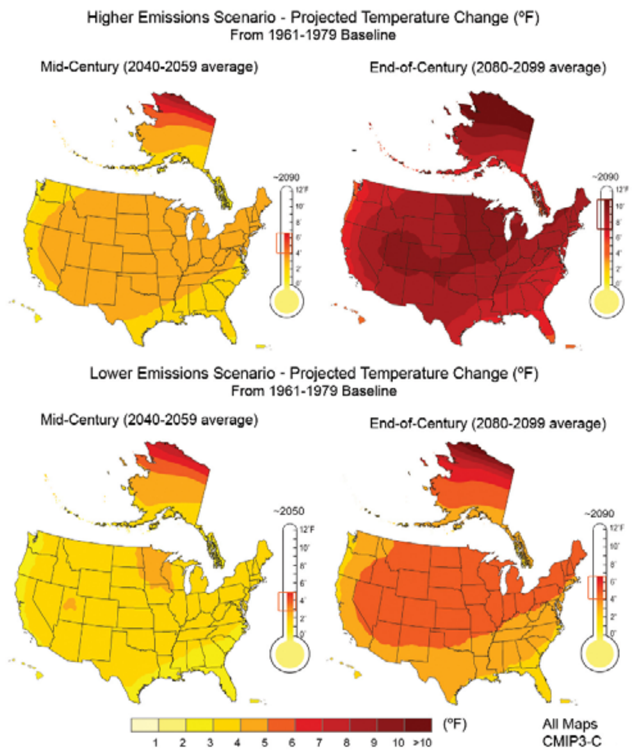

Figure 2. Projected temperature change for mid-century (left) and end-of-century (right) in the United States under higher (top) and lower (bottom) emissions scenarios. The brackets on the thermometers represent the likely range of model projections, though lower or higher outcomes are possible. *Source*: US GCRP 2009.

For the purposes of this paper, we have focused on the two climate extremes depicted above: hot/dry and cold/wet. At the time of writing, the US is experiencing these exact extremes with the polar vortex impacting the Northeast, and a severe drought effecting the Southwest. However, generally strategies for building resiliency at each extreme encompass strategies for those in less impacted geographies as well.

The resiliency strategies compiled below represent a subset that applies specifically to existing buildings. Providing measures in this way is intended to inform building owners and operators in the decision making process when assessing building maintenance and retrofit investments in light of an evolving climate risk scenarios.

Assessing Risk

Prior to investing in the strategies identified herein, the risks specific to each location need to be assessed, i.e. each building owner will need to determine which buildings should not be upgraded as they will be sold, relocated, abandoned or otherwise divested due to risk-related devaluation.

In order to assess the risk associated with climate change impacts on existing building stock, building owners and operators will need to understand the hazards presented by climate change, the potential impact, and their vulnerability. Our research found only one free tool for non-residential building owners to assess resiliency: the Integrated Rapid Visual

Screening of Buildings published by the Department of Homeland Security. This program gives a score across multiple risk attributes. "Ratings are given in the summary for the components of resilience: robustness, resourcefulness and recovery" (Koch 2014).

The simple formula: Hazard x Vulnerability = RISK, is a common way to ascertain the degree of a risk, and can be used to assign a risk "score" to a building. Regardless of the methodology employed, having a common means of comparing buildings against one another can help prioritize the use of limited investment capital.

The six climate hazards and their calculated risks summarized in Table 1 below are the highest priorities for the built environment (Larsen et al. 2011).

Table 1. Hazards and risks to hotter/drier and colder/wetter climates

Climate impact	Hazard	Risk to hotter/drier climates	Risk to colder/wetter climates
Temperature	By 2100, the average US temperature is projected to increase from 4°F to 11°F (US GCRP 2009).	Increased summertime cooling loads, refrigerant tonnage necessary to achieve comfort levels, and brownouts	
Water/ Precipitation	Northern areas will become wetter, southern areas will become drier. Precipitation is expected to fall as rain rather than snow. For each 1.8°F increase in tropical sea surface temperatures, the rainfall rates of hurricanes may increase by 6-18% and the wind speeds of the strongest hurricanes may increase by 1-8% (US GCRP 2009).	Inadequate irrigation water supply, less ability to rely on cooling system water, more frequent water restrictions or rationing	Increased risk of flooding or water damage, overload to stormwater systems, and higher flood insurance rates
Coastal erosion / Sea level rise	Sea levels rose by roughly 8" over the past century. Recent satellite data shows that sea levels rose roughly double that over the last 15 years. Current projections show a range of sea level rise of 6' to 10' by 2100. (IPCC 2007a).	Decreased property value, increased flooding of low-lying areas, increased erosion	
Air quality	Half of all Americans (158 million people) live in counties where air pollution exceeds national health standards. Higher temps make it more challenging to meet air quality standards, especially for ground-level ozone (a component of smog) (US GCRP 2009).	Decreased capacity for natural ventilation, increased need for filtration, increased incidence of health impacts	
Pests	Rising temperatures allow insects and pathogens to expand their ranges, and allows more insects to survive winters (US GCRP 2009).	Increased risk of damage from insects to vegetation, landscaping and insect borne disease	
Fire	There has been a fourfold increase in large wildfires in recent decades, with greater frequency, longer durations, and longer seasons (US GCRP 2009).	Increased wildfire damage in forests, increased fire insurance rates	

Methodology

In an effort to identify resiliency strategies for existing buildings, we reviewed multiple reports, papers, and a few specific local efforts that called out strategies for improving resiliency in the built environment. Some of these efforts were focused on community-scale planning, but most were targeted to non-residential new construction and existing buildings. From this information—as well as the authors' professional experience—we extracted and classified strategies applicable to existing non-residential buildings into seven primary categories: Energy Systems, Water Systems, Envelope, Equipment, Site/Landscaping, Materials, and Operations. Once categorized, we further defined each strategy across topics relevant to their potential impact on non-residential building owners.

Resiliency Strategies

Once a building owner/operator has assessed the level of risk they face given future climate conditions and identified to which hazards they are most vulnerable, they can implement strategies (as listed in the sections below) that build adaptive capacity in response to those specific risks.

Energy Systems

A critical vulnerability to building owners/operators will be the impact of climate change on energy supply and demand. They will need to understand the various impacts of future energy use in order to determine overall impact on operating expenses and asset value. Above all else, energy costs continue to rise and adjustments to energy use will have a direct impact on net operating income.

There is the issue of grid reliability and infrastructure stability, which hit close to home for many when Hurricane Sandy hit in 2012. The impact of Sandy not only caused hundreds of deaths and billions of dollars of damage, it also left thousands without power for weeks (UGC 2013). Since we rely on the built environment for shelter, and existing building stock is not designed to be passively operated, it is critical that existing buildings are improved to provide power during emergencies.

Related to grid reliability is the "Energy/Water Nexus": the amount of energy required for treating and distributing water/the amount of water required for generating electricity. As water supply is compromised and local jurisdictions define essential and non-essential water use, it will become increasingly important to install systems and use energy sources that do not require water for cooling.

Finally, climate predictions indicate that warming trends across winter and summer will result in significant increases in cooling loads (Perez 2009). In a 2006 report by the California Energy Commission, predictions show a 20.3% increase in annual electricity use and a 10.3% increase in peak demand given worst case scenarios for greenhouse gas (GHG) emissions (Franco 2006).

The following strategies relate specifically to energy using or generating systems. Measures related to energy using equipment and building envelope are addressed elsewhere in this document.

Table 2. Resiliency strategies for energy systems

Strategy	Description
GENERAL SAFETY	
Electrical surge protection	Protect electrical services with surge protection installed in accordance with NFPA 70 and the manufacturer's installation instructions. Critical electronic equipment should be prioritized. *Source:* FEMA 2013, IBHS 2010.
Emergency lighting	Provide emergency lighting with backup power supply for all stairwells, exit

	access corridors, and security purposes in the event of grid failure. *Source:* UGC 2013, Linnean Solutions 2013, Larsen et al. 2011.
PASSIVE ENERGY SAVINGS	
Cross ventilation	Cross ventilation may allow for the building to be occupied without AC during power failure. *Source:* Larsen et al. 2011.
Ceiling fans	Electric fans increase air speed, providing thermal comfort and reducing energy used for AC. *Source:* Larsen et al. 2011.
Evaporative cooling towers, shower towers, passive cooling	Use evaporative cooling towers to induce a down draft and naturally cool air. *Source:* Larsen et al. 2011.
Daylighting	Make natural light available in lieu of electric lighting and install automated controls to optimize. *Source:* Larsen et al. 2011.
ENERGY SYSTEMS AND CONTROLS	
Thermal energy storage	Thermal storage mediums include water and thermal masses. *Source:* Larsen et al. 2011.
Thermal zoning	Adjust zoning in rooms with similar temperature requirements based on use, schedule, or time spent in the space. *Source:* Larsen et al. 2011.
Energy Management System (EMS)	Install EMS to monitor and control equipment—priority given to the equipment with the most electrical demand. *Source:* Larsen et al. 2011.
Fire barriers and partitions	Ducts and air transfer openings of fire barriers/partitions are typically required to have fire dampers when penetrating the barrier. *Source:* IBHS 2010.
BACKUP/EMERGENCY POWER SUPPLY	
Prioritization of needs	Prioritize which electrical equipment will run on backup power. *Source:* Linnean Solutions et al. 2013, UGC 2013.
Backup generators	Cogeneration and solar power systems should be designed to run during blackouts. *Source:* UGC 2013.
Critical system backup	Critical systems should be backed up with renewable power generation, a generator, or battery backup system. *Source:* Larsen et al. 2011.
Generator location	Locating backup generator above flood level ensures that backup systems can operate in the event of a flood. *Source:* Larsen et al. 2011.
Add backup fire safety communication	Provide backup power sources for fire and life safety communications systems. *Source:* UGC 2013.
Install cogeneration and/or on-site photovoltaics	Consider on-site generation for backup power. *Source:* UGC 2013.
Add quick connects for backup power	Add hookups for temporary generators and boilers. *Source:* FEMA 2013, UGC 2013.

Water Systems

To understand the impacts of climate change on the water supply, one must first understand the impacts at the regional scale. Extensive research has been conducted on this issue, as natural systems and human populations depend on an adequate water supply. Projections indicate increased precipitation at higher latitudes, more intense and frequent droughts, and depleted melted snow-fed watersheds (Larsen et al. 2011).

In the hotter/drier climates, this most likely means more frequent and more stringent water use restrictions or water rationing during drought conditions for building owners. We have already seen this during the 2013-2014 winter drought in California. In Sacramento, the "Stage 2 Water Plan" requires those who live and work in Sacramento to reduce their water usage by 20-30%. In wetter/colder climates, building owners/operators are most likely facing the need for increased stormwater management. In a study conducted by the Rock Creek Basin in Oregon, researchers found that both compact and sprawling development patterns increase annual runoff by over 5%, which exposed the buildings to flooding and water damage.

Table 3. Resiliency strategies for water systems

Strategy	Description
WATER EFFICIENCY AND REUSE	
Install gray water system	Collected gray water can be used for sewage conveyance, landscaping, and cooling towers. Source: FEMA 2013, Linnean Solutions et al. 2013.
High efficiency fixtures	Water fixtures that reduce water flow help conserve potable and reused water in areas. Source: FEMA 2013, Larsen et al. 2011.
Educate occupants on water saving techniques	Encourage occupants to turn water flow off while brushing teeth or during other cleaning activities, and running the dishwasher and washing machine only when they are full. Source: FEMA 2013.
Retrofit water supply systems	Improve water supply and delivery systems to eliminate breaks and leaks. Source: FEMA 2013.
HVAC condensate capture	Condensate from AC units can be used for irrigation, cooling towers, or cooling building equipment. Source: Larsen et al. 2011.
EMERGENCY WATER SUPPLY	
Rainwater capture	Capture rainwater from downspouts for reuse. Source: FEMA 2013, Larsen et al. 2011.
Sewage backflow prevention	Installing back flow prevention valves on building sewage lines can prevent sewage from entering the building. Source: Larsen et al. 2011, UGC 201.
Supply drinking water without power	Provide at least one operable-without-power fixture per 100 occupants in an accessible common area of the building (not in bathroom). Clear signs must identify the location of these fixtures. Source: UGC 2013.
Ensure toilets and sinks work without power	At least one faucet and one toilet in each bathroom must be capable of operating without external electrical power for at least two weeks. Source: UGC 2013.
Enhance building water reserves	Maintain existing water towers and consider adding water storage. Source: UGC 2013.
WATER SUPPLY PLANNING	
Monitor water supply	Monitor the water supply and regularly check for leaks to minimize water supply losses. Source: FEMA 2013.
Plan for future drought events in your area	Develop a drought emergency plan including identifying secondary water sources/agreements. As needed, design and build water tanks or wells for use in times of water outage. Source: FEMA 2013.
Protect against freezing pipes	Protect pipes via insulation of water pipes in vulnerable outside walls, attics, etc. Letting a faucet drip (and capturing the water if possible!) during extreme cold weather can prevent buildup of excessive pressure in the pipeline and avoid bursting. Source: FEMA 2013.

Envelope

Addressing the building envelope is critical for buildings in all climate regions, as the envelope defends against outside conditions while maintaining interior conditions. A durable, well-constructed building envelope can reduce risk of moisture intrusion and long term wind-related damage; however, a less durable but easier to maintain exterior might expedite recovery after an extreme weather event.

Availability of outside air for effective ventilation may also be compromised given rising temperatures. Buildings that use nighttime outside air to cool space may have to condition the air to meet thermal comfort conditions. Ground-level ozone, which is expected to rise with higher temperatures, will also limit the option for using outside air for cooling (Larsen et al. 2011).

Table 4. Resiliency strategies for building envelope

Strategy	Description
ROOF	
High albedo roofing/ Solar reflectance index (SRI)	Install roofing materials with a high SRI or similar prescriptive level of impact. *Source:* FEMA 2013, IBHS 2010, Larsen et al. 2011, Linnean Solutions et al. 2013, UGC 2013, US EPA 2013.
Green roof	Install green roof system. *Source:* FEMA 2013, Larsen et al. 2011, US EPA 2013.
Oversized roof drainage	Roof leaders, gutter downspouts, and drains are all sized for historical rain rates and not future predictions. *Source:* Larsen et al. 2011, Linnean Solutions et al. 2013.
Roof drain protection	All roof drains on low-slope roofs located in severe exposure areas in Figures 1 and 2 shall have heating strips (heat trace) installed around them. *Source:* IBHS 2010.
Wind resistance of roofing material	Consider wind implications on roofing material (including aggregate), slope, edge design, rooftop photovoltaics, and attachment method. *Source:* IBHS 2010.
Protect from hail damage	Minimize damage through structural bracing, shutters, laminated glass, hail-resistant roof coverings or flashing, and improved roof sheathing to prevent hail penetration. Contacting the Insurance Institute for Business and Home Safety (IBHS) to learn more. *Source:* FEMA 2013.
Retrofit roofs for higher snow loads	Retrofit to withstand snow loads and prevent roof collapse. *Source:* FEMA 2013.
Fire-resistant construction techniques	Use Class A Roofs in hot/dry climates. Where feasible use fire stop eave ends to preclude entry of flames or embers. *Source:* FEMA 2013, IBHS 2010.
SIDING & WINDOWS	
Mold resistant materials	To prevent negative health impact of mold, ensure that building envelope consists of materials that withstand water damage. *Source:* Larsen et al. 2011.
Fire-resistant construction techniques	Enclose foundations in wildfire-prone areas, to stop from exposing undersides to blown embers or other materials. Use functional shutters on windows. *Source:* FEMA 2013.
Non-combustible siding	Increase fire resistance by replacing exterior siding with non-combustible materials. *Source:* Larsen et al. 2011.
Replace vinyl siding	If exposed to hurricanes, wind, wind-born debris, or hail consider replacing with a more durable, wind- and debris-resistant material. *Source:* IBHS 2010.
Prevent wind damage to windows	Eliminate window stops on windows over a certain height; instead use windows that "pop out," opening along all four sides. *Source:* Larsen et al. 2011.
Prevent damage from seismic events	Brace generators, elevators, and other vital equipment. Identify critical lifeline systems. Use flexible piping when extending water, sewer, or natural gas service. Install shutoff valves and emergency connector hoses where water mains cross fault lines. Install window film to prevent injuries from shattered glass. Anchor rooftop-mounted equipment (i.e., HVAC units, satellite dishes, etc.). *Source:* FEMA 2013.
Prevent wind damage	Install impact-resistant windows in wind-prone areas. Install rain- and impact-resistant louvers. Recommend anchoring framing to foundations and strengthening foundations and basements in existing buildings. Protect against wind with structural bracing, straps and clips, anchor bolts, reinforced pedestrian and garage doors, window shutters, waterproof adhesive sealing strips, interlocking roof shingles, improved nailing patterns, tie-downs with anchors, and ground anchors. Detach carports and open coverings that can serve as a wind sail. Upgrade to ductile infrastructure. Retrofit gable end walls to eliminate wall failures in high winds. Anchor roof-mounted heating, ventilation, and air conditioning units. Avoid placing flag poles or antennas near buildings. *Source:* FEMA 2013, Linnean Solutions et al. 2013, UGC 2013.
PLANNING	
Analyze wind risks	Conduct wind analysis that includes: Risk for falling debris based on the age, construction, height, and occupancy of your building; Effects of wind if

	building is raised, supported by columns, or moved in order to address flood hazard concerns; and The benefits of installing and maintaining a weather station on your building. Install natural features (e.g., trees) as wind buffers. Consider opening windows, when safe, to allow wind to pass through in a controlled way. *Source:* FEMA 2013, UGC 2013.
Lightning protection	Install, upgrade, and maintain lightning protection devices and methods, such as lightning rods and grounding, on communications infrastructure and other critical facilities. *Source:* FEMA 2013.
Flood-proof structures	Wet flood-proof basements; allows for controlled flooding to balance exterior and interior wall forces and discourages structural collapse. Using water resistant paints or other materials to allow for easy cleanup after floodwater exposure in accessory structures or areas below an elevated residential structure. Dry flood-proof by strengthening walls, sealing openings, or using waterproof compounds or plastic sheeting on walls to keep water out. *Source:* FEMA 2013, Linnean Solutions et al. 2013.
Exterior flood protection and alternative access	Plan for temporary flood barriers or shields, their supports and attachments. Check with local laws related to the public right-of-way, temporary stairs, and ramps to be used to access exits above the flood line. *Source:* UGC 2013.
PASSIVE STRATEGIES	
Passive survivability	Survivability can be achieved through both passive—typically combining a highly energy-efficient thermal envelope with passive heating, cooling, ventilation, and daylighting strategies—and active means, such as on-site renewables and rainwater harvesting. *Source:* US EPA 2013.
Maintain habitable temperatures without power	Protect passive survivability with improved insulation and sealing of a walls, windows, and roof. *Source:* UGC 2013.
Shading devices	These can reduce solar heat gain in the summer and allow for heat gain in the winter, reducing peak electrical demand and annual cooling requirements. *Source:* Larsen et al. 2011.
Insulation	Well-designed insulation systems reduce conduction through thermal envelope. This reduces interior temperature, peak electrical demand, and annual cooling requirements. *Source:* FEMA 2013, Larsen et al. 2011, Linnean Solutions et al. 2013.
Draftstopping	Draftstopping to be provided in floor/ceiling spaces, attics, mansards, overhangs, or other concealed roof spaces. *Source:* IBHS 2010.

Equipment

In addition to a building's energy system, equipment systems need to be considered for a building to be resilient. Whether intended to promote life and safety (fire sprinklers) or central to business operations (telecommunications), equipment should be located where it is less susceptible to intermittent disruption and damage. Building equipment can be vulnerable to water damage and should be placed above flood zone. Building owners should also consider installing systems that allow for redundancy in the event of a power outage. Also, sensors and alarms can be used to alert occupants in the event of a disaster, but must be protected from damage to perform that function properly.

Table 5. Resiliency strategies for equipment.

Strategy	Description
EQUIPMENT PLACEMENT AND PROTECTION	
Relocate and protect building systems	Relocate vulnerable building elements (electrical services, fire protection systems, compressed gas or hazardous material tanks, and vent piping) above flood elevations in flood zones. Source: FEMA 2013, UGC 2013.
Buildings and building	Elevate building systems, particularly telecommunications systems and fuel oil storage.

systems	Protect flammable items (e.g., propane tanks) Source: FEMA 2013, UGC 2013.
System redundancy	Redundant systems may reduce efficiency but may also be necessary for resilience (i.e., dividing cooling loads across several compressors or heating loads across several boilers). Source: Larsen et al. 2011.
EQUIPMENT, SENSORS AND ALARMS	
Particulate matter removal	Where feasible, given the increase of fan energy and size of equipment respectively, consider higher Minimum Efficiency Rating Value (MERV) ratings of 8-13. Source: IBHS 2010.
Variable Frequency Drive (VFD)	Consider installing VFDs when retrofitting. Source: Larsen et al. 2011.
Insulate refrigeration equipment	Insulate refrigeration equipment. Source: Larsen et al. 2011.
Manual fire alarm boxes	Install manual fire alarm boxes when the building is provided with automatic sprinkler systems. Source: IBHS 2010.
Wildfire mitigation techniques	Install fire mitigation systems such as interior and exterior sprinkler systems. Install and maintain smoke detectors and fire extinguishers on each floor of homes or other buildings and at least one outside in wildland areas. Source: FEMA 2013, IBHS 2010.
CO2 Sensors	CO2 monitors for all occupied and ventilated spaces and at least one monitor outside the building. Source: IBHS 2010.

Site/Landscaping

The building location and the makeup of its immediate surroundings can have substantial impact not only on its risk but its potential for resiliency. Extensive landscaping can be useful in mitigating temperature extremes and providing space for stormwater control. Buildings without landscaping in a dense urban location can be better protected from wind damage and more accessible to emergency personnel.

Table 6. Resiliency strategies for site/landscaping

Strategy	Description
VEGETATION	
Climate appropriate landscaping	Consider future climate conditions when planning landscaping; a diverse palate of native plants is preferable. Replace flammable vegetation with less flammable species. *Source:* FEMA 2013, Larsen et al. 2011.
Plant wind and flood resistant trees	In waterfront areas consider wind and salt-tolerant trees and regular tree pruning. *Source:* UGC 2013.
Drought-tolerant landscape	Incorporate drought-tolerant or xeriscape practices. *Source:* FEMA 2013.
Irrigation scheduling	Establishing an irrigation time/scheduling program or process so that food and tree species are prioritized. Through incremental timing, irrigate at different times so all water is not consumed at the same time. *Source:* FEMA 2013.
Redirect landscaping sprinklers	Remove/Turn off landscape sprinklers that wet exterior wall surfaces. *Source:* IBHS 2010.
Defensible Space around structures and infrastructure	Create fire buffers around structures through the removal or reduction of flammable vegetation, including vertical clearance of tree branches. Create defensible zones around power lines, oil and gas lines, and other infrastructure systems. Safely dispose of yard and household waste rather than open burning. Remove dead or dry leaves, needles, twigs, and combustibles from roofs, decks, eaves, porches, and yards. Safely use and store necessary flammable materials, including machine fuels. Approved safety cans should be used for storing gasoline, oily rags, and other flammable materials. Firewood should be stacked at least 100 feet away and uphill from homes. *Source:* FEMA 2013.

STORMWATER MANAGEMENT	
Minimize impervious surfaces	Reduce runoff with surfaces that are permeable and allow for stormwater infiltration. Consider permeable repaving materials (including their cost, durability, and absorption capability), and/or the possibility of changing the angulation of street/sidewalk in flood-prone areas near bodies of water.*Source:* FEMA 2013, Larsen et al. 2011, UGC 2013.
Elevate or retrofit structures and utilities	Elevate structures so that the lowest floor, including the basement, is raised above the base flood elevation. Raise utilities or other mechanical devices above expected flood levels. Use tank-less water heaters in limited spaces. *Source:* FEMA 2013.
Retention ponds	Consider installing retention pond(s). *Source:* Larsen et al. 2011.
Constructed/Natural wetlands & bioswales	Install slope gradations for the capture and treatment of stormwater. *Source:* Larsen et al. 2011.
Flood debris mitigation	Install backflow valves to prevent reverse-flow flood damages. Secure debris, propane tanks, yard items, or stored objects that may otherwise be swept away, damaged, or pose a hazard if picked up and washed away by floodwaters. *Source:* FEMA 2013.
Improve stormwater drainage system capacity	Increasing drainage or absorption capacities with detention and retention basins, relief drains, grassy swales, roadside drain widening/dredging or rerouting, logjam and debris removal, extra culverts, or flood gates and pumps. *Source:* FEMA 2013.
Conduct regular maintenance for drainage systems and flood control structures	Perform regular drainage system maintenance, such as sediment and debris clearance. Routinely clean and repair stormwater drains (do not rely solely on Public Works). Incorporate ice jam prevention techniques as appropriate. *Source:* FEMA 2013.
HARDSCAPE	
Reduce urban heat island effect	Increase tree plantings around buildings to shade parking lots and along public rights-of-way. Cover outside and/or underground parking lots with non-vegetated devices such as photovoltaics. *Source:* FEMA 2013, Larsen et al. 2011, Linnean Solutions et al. 2013.
Green, complete streets	Incorporating green infrastructure elements (such as pervious paving, landscape buffers, and oversized tree wells) within the right-of-way absorbs polluted runoff and helps manage stormwater. *Source:* US EPA 2013.
OTHER	
Remove existing buildings & infrastructure from erosion areas	To prevent damage from erosion, consider acquiring and demolishing or relocating at-risk buildings and infrastructure and enforcing permanent restrictions on development after land and structure acquisition. *Source:* FEMA 2013.
Consider the IWUIC recommendations for buildings not in urban zones	The International Wildland-Urban Interface Code (IWUIC) regulates exposed exterior construction on the walls, roof, decks, soffit, and other exposed exterior surfaces as well as mandating a radius around the structure that must be kept clear of trees, shrubs, brush, etc. *Source:* IBHS 2010.
Bollards	Where smash and grab theft may be accomplished with a vehicle, consider installing bollards. *Source:* IBHS 2010.

Operations

Educating occupants about the associated risks of climate change is key to improving resiliency. In addition, building owners can look to energy efficiency to monitor performance and ensure systems can operate given extreme climate conditions.

Table 7. Resiliency strategies for operations

Strategy	Description
Safeguard toxic materials stored in flood zones	Take floods and other extreme weather events into consideration with hazardous/toxic material storage methods and emergency management plans. *Source:* UGC 2013.
High performance fire safety	Combine active and passive protection/suppression without allowable design-hour reductions from fire sprinklers to reasonably guarantee that fire does not spread past the area or room of origin. *Source:* IBHS 2010.
Minimum critical radiant flux	Interior floor finish and floor covering materials in exit enclosures, exit passageways, and corridors shall not be fire resistant. *Source:* IBHS 2010.
POLICIES AND EDUCATION	
Inform occupants of Emergency Action Plans	Provide occupants with technical documents on mitigation options and a copy of the facility's Emergency Management Plan. *Source:* Authors 2014.
Increase awareness of extreme temperatures	Educate occupants regarding the dangers of extreme heat/cold and the steps they can take to protect themselves when extreme temperatures occur. *Source:* FEMA 2013.
Flexible dress codes/scheduling	Flexible dress codes and schedules allow for occupants to adapt to warmer temperatures by either dressing lighter or avoiding working during hotter parts of the day. *Source:* Larsen et al. 2011.
Increase earthquake risk awareness	Develop an outreach program about earthquake risk and mitigation for occupants. Educate occupants on safety techniques to follow during and after an earthquake. *Source:* FEMA 2013.
Winter health awareness	Develop an educational effort that produces and distributes family and traveler emergency preparedness information about severe winter weather hazards, include in driver education classes and materials. Encourage occupants to install carbon monoxide (CO_2) monitors and alarms. Educate occupants that all fuel-burning equipment should be vented to the outside. *Source:* FEMA 2013.
Flood insurance	Buy flood insurance. *Source:* FEMA 2013.
Flood/Sea level rise risk awareness	Annually distributing flood protection safety pamphlets/brochures to occupants, including dangers of driving on flooded roads. *Source:* FEMA 2013.
Allow flexible work arrangements	Allow employees to work from home during extreme weather events when feasible. *Source:* Authors 2014.
Participate in Firewise Program	Joining the "Firewise Communities/USA" recognition program sponsored by the National Wildlife Coordinating Group (www.firewise.org). *Source:* FEMA 2013.
Provide Information on Retrofitting	Develop an outreach program to encourage occupants to secure furnishings, storage cabinets, and utilities to prevent injuries and damage at home and work. *Source:* FEMA 2013.
ON-GOING ENERGY EFFICIENCY	
Energy modeling	Helps to understand how a building will operate given future climate conditions. *Source:* Larsen et al. 2011.
Building Information, Operations & Maintenance (O&M) Manuals	Supply O&M manuals so building owners/operators are properly informed about the best ways to operate their building and its systems in order to achieve optimum building performance. *Source:* AUS GBC.
Ongoing monitoring and metering	Track water and energy use over time. *Source:* AUS GBC.
Tuning, commissioning and retro-commissioning	Continuous and comprehensive tuning process and thorough reviews of building systems in comparison to operational requirements. *Source:* AUS GBC, Larsen et al. 2011.
PLANNING	
Emergency preparedness plan	Building owners/operators should plan and organize with occupants to reduce potential harm. Encouraging occupants to stock the necessary items and practice how to respond during a disaster. Include a communications plan. *Source:* Larsen et al. 2011, Linnean Solutions et al. 2013.
Pre-negotiate	As part of emergency planning, building owners/operators should identify

emergency recovery agreements	service providers and pre-negotiate emergency recovery agreements. *Source:* UGC 2013.
Improve disaster preparedness	Purchase hazard insurance not as an alternative to mitigation, but rather to add financial protection if damage does occur. *Source:* FEMA 2013.
Operating during an emergency	Investigate local laws related to liability risks for maintaining building operations during an emergency. *Source:* UGC 2013.
Identify emergency inspectors	Identify city-approved emergency inspectors and include contact information in the emergency plan. *Source:* UGC 2013.
SHELTER	
Areas of refuge	Areas of refuge (safe, fortified gathering places) are important to geographic areas where tornados or hurricanes are more likely. *Source:* Larsen et al. 2011, Linnean Solutions et al. 2013.
Consider adding/ maintaining safe rooms.	Consider all likely hazards in the region (tornados, earthquakes, hurricanes, flooding) when determining the location of a safe room. *Source:* FEMA 2013, IBHS 2010.

Materials

Flooding and fire damage should be taken into account when considering materials within the building. Materials that are susceptible to moisture damage can also develop mold, which impacts indoor air quality and occupant health.

Table 8. Resiliency strategies for materials

Strategy	Description
Safeguard toxic materials stored in flood zones	Take floods and other extreme weather events into consideration in hazardous/toxic material storage methods and emergency management plans. Source: UGC 2013.
High performance fire safety	Combine active and passive protection/suppression without allowable design-hour reductions from fire sprinklers to reasonably guarantee that fire does not spread past the area or room of origin. Source: IBHS 2010.
Minimum critical radiant flux	Interior floor finish and floor covering materials in exit enclosures, exit passageways, and corridors shall not be fire resistant. Source: IBHS 2010.
Combustible decorative materials	Reduce amount of flammable decorative material. Keeping flammables, such as curtains, secured away from windows or use heavy fire-resistant drapes. Source: FEMA 2013, IBHS 2010.

Conclusion

Many existing buildings in North America are at risk due to climate change impacts in the near term. Adequate tools are needed for building owners and operators to assess risk and identify strategies for protecting existing buildings from these climate hazards. In general, resiliency strategies fall into three broad categories: prevent or reduce the amount of damage, protect life and assets, and plan for expedited recovery. This report serves as a first step toward effectively sorting and communicating preventative actions for mitigating climate change impacts on existing buildings. Building owners/operators are advised to consider a building's risk profile prior to making capital improvements and implementing resiliency strategies. In addition, local governments can support the effort by including climate risk assessments as part of the permitting process, and by providing tools for building owners to conduct climate risk assessments on existing facilities. As this effort evolves, more work is needed to document successful recovery efforts of buildings involved in disasters related to climate change.

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