

Assessing Climate-Induced Degradation of HVAC, Solar PV, Electrical and Control Systems in Buildings

Abstract. Canada's accelerated warming, nearly double the global average, has heightened the frequency and severity of extreme climate events, challenging the reliability and long-term performance of building systems. Events like the 2021 British Columbia heat dome exposed existing infrastructure to extreme thermal stress. This paper examines the impact of climate change on the durability and performance of building components, particularly Heating, Ventilation, and Air Conditioning (HVAC) systems, solar photovoltaics (PV), electrical, and control systems in buildings. A review of the literature identifies stressors such as extreme temperatures, thermal cycling, and excessive humidity. Key risks include reduced heating and cooling capacity during temperature extremes, accelerated HVAC wear, and solar PV performance losses/degradations. The analysis highlights heat and moisture as significant threats to electrical and control systems and highlights the need for updated inspection protocols. Finally, the paper advocates for climate-resilient design in Canadian building strategies to ensure long-term performance, affordability, adaptability, and occupant safety.

Keywords: Durability of Building Systems, Climate Change Impacts.

1 Introduction

Canada's climate is warming at nearly twice the global average, with the mean annual temperature increasing by about 2.4 °C since the mid-20th century [1]. This change has led to more frequent and intense heat waves, with some climate events occurring 2 to 10 times more often than in a non-warming situation. Extreme weather conditions, including heat waves, wildfires, and heavy precipitation, have strained buildings and communities, exemplified by the 619 heat-related deaths during the 2021 British Columbia heat dome [2].

Traditional designs of building mechanical and electrical systems, including Heating, Ventilation, and Air Conditioning (HVAC) and photovoltaic (PV) systems, relied on historical climate data with the assumption of a stationary climate [3]. However, the acceleration of warming trends has made these assumptions gradually outdated, putting additional stress on systems that can lead to degradation and reduced performance.

Despite advancements in energy efficiency, durability and service-life considerations for building components have received insufficient attention in light of climate change. The frequency of extreme heat, cold, and thermal variability raises the risk of premature system failures and increased maintenance needs [4]. To address these challenges, an integrated understanding of how climate stressors impact system performance is essential.

This overview examines the impacts of climate change on the durability and performance of building energy systems, focusing on HVAC, solar PV, electrical, and control systems in Canada. A review of relevant literature identifies key climatic stressors and evaluates their implications for reliability and maintenance. The analysis highlights the importance of incorporating climate-resilient design strategies to ensure long-term performance, affordability, and occupant safety in evolving climate conditions.

2 Research Methodology

This research uses a systematic methodology to assess the durability of building energy systems under climate change. Figure 1 illustrates the research methodology framework, connecting climate change drivers and stressors with evidence review and building system assessment to derive resilience and adaptation.

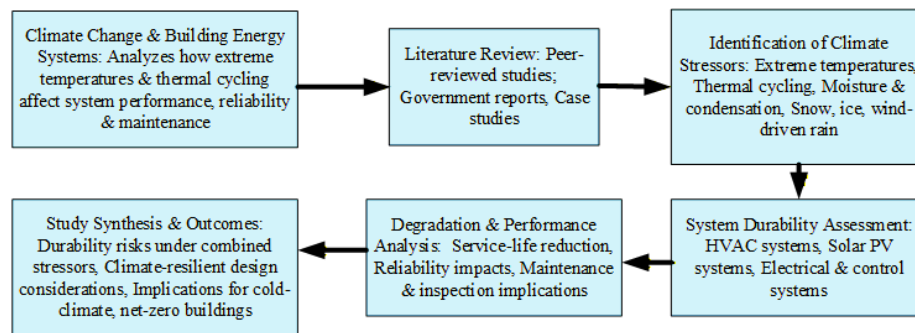


Fig. 1. Flowchart outlining the research methodology

3 Climate Change Stressors Affecting Building Systems

The changing climate is imposing various stressors that significantly impact the durability and service life of building materials and systems. Extreme temperatures, both hot and cold, are becoming more frequent, putting thermal stress on building envelopes, HVAC, electrical and control systems [4,5]. This leads to material expansion and contraction, reduced efficiency, more maintenance, and ultimately shorter service life.

Increased thermal cycling, driven by both diurnal and seasonal changes, exacerbates material fatigue, promotes micro-cracking, and stresses joints. This cycling can also accelerate the degradation of solar PV modules and HVAC systems while facilitating moisture ingress that causes freeze-thaw damage [6].

Changes in precipitation patterns and rising humidity levels heighten the risk of condensation within building assemblies, leading to moisture intrusion that can cause

corrosion, insulation deterioration, mold growth, and system failures, particularly in high-performance, airtight designs net zero energy buildings [4,7].

Cold-climate structures are also facing greater risks from extreme snow loads, ice formation, and heavy rain, which threaten structural integrity and drainage system issues [3]. Traditional design methods, based on historical weather patterns, are increasingly inadequate due to climate uncertainty, complicating service life predictions and maintenance planning.

4 Climate Stressors Impacts on HVAC, Solar PV, and Electrical and Control Systems

HVAC and Solar PV systems are among the most climate-exposed and operationally intensive components in buildings, making their reliability and durability highly sensitive to changing environmental conditions. This section highlights emerging concerns related to climate change in HVAC, solar PV, and other electrical and control systems [8,9].

Increased Cooling Demand and Operational Stress. Traditionally in Canada, HVAC systems have been designed primarily to meet heating requirements, with cooling treated as a secondary consideration. As a result, many older buildings were constructed without any dedicated cooling systems. For example, in British Columbia, approximately 55% of households currently have no air conditioning (AC) [10]. However, climate change is driving a significant increase in cooling demand in all areas, particularly during prolonged heat events. Studies have shown that higher cooling loads for an extended period led to longer AC operating hours, increased compressor cycling, and elevated thermal stress on mechanical components, which collectively accelerate material fatigue and component failure [5,8]. These effects are particularly evident in existing buildings where systems were not designed or sized for prolonged high cooling demand due to climate change.

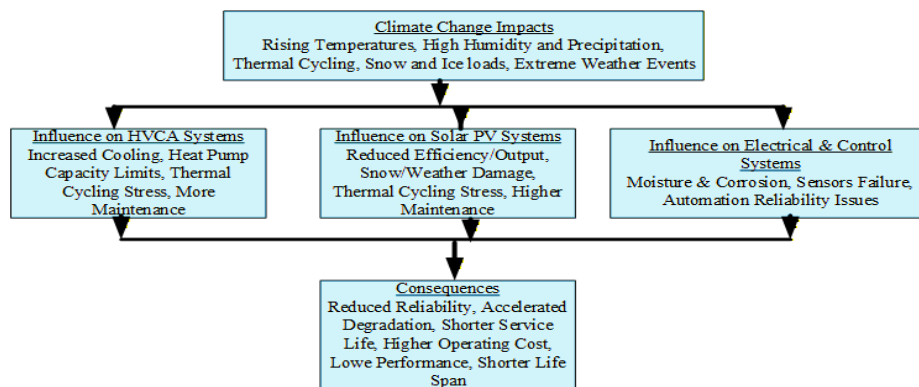


Fig. 2. Impacts of climate change stressors on building energy systems

Impact of Thermal Cycling. Climate-induced temperature variability has increased the frequency of thermal cycling, particularly in hybrid HVAC systems that switch between heat pumps and auxiliary heating sources, such as natural gas furnaces/boilers. Frequent on–off cycling and mode switching introduce mechanical and thermal stresses that accelerate degradation of compressors, valves, heat exchangers, and control components [11]. While hybrid systems offer operational flexibility and resilience, their long-term durability depends on appropriate control strategies, adaptability to extreme events, component robustness, and proper maintenance [12].

Maintenance, Reliability, and Service-Life Implications. The combined effects of increased cooling demand, temperature extremes, and thermal cycling have direct implications for HVAC maintenance and reliability. Evidence from field studies and industry reports indicates that climate stress can increase maintenance frequency, shorten inspection intervals, and reduce expected equipment lifespans compared to conventional assumptions [3,4]. These impacts challenge traditional service-life models and highlight the need for climate-adjusted durability assessments when designing or retrofitting HVAC systems in Canadian buildings.

Solar PV Systems Performance Impacts. In recent decades, Canada has seen significant growth in the adoption of solar PV technology in buildings, driven by lower costs, improved efficiency, supportive government policies, and heightened awareness of global warming. However, climate change poses many challenges for solar PV systems and mounting structures, including rising temperatures that may reduce efficiency and cause greater thermal expansion and contraction of materials, which can stress connections, fasteners, and framing over the system's decades-long lifespan [6,7]. All these factors influence solar PV system and components degradation, durability, and raise performance and maintenance concerns. While Canada's cold climate generally benefits solar PV operation, the need for resilient system design and adaptation strategies is crucial to address climate-evolving snow loads and ice-related stresses.

Electrical and Control Systems Moisture sensitivity. Electrical and control systems are highly vulnerable to moisture intrusion caused by increased climate-induced humidity, mold, condensation, and wind-driven precipitation. In high-performance, airtight buildings, reduced drying potential can worsen moisture accumulation around electrical wiring, junction boxes, sensors, and control panels. Extended moisture exposure accelerates corrosion, degrades insulation, and increases the likelihood of short circuits and intermittent failures, thereby undermining system reliability over time [13,14].

Reliability of sensors and controls. Contemporary buildings are increasingly dependent on sensors, controllers, and communication devices to enhance the performance of HVAC and energy systems. These elements are vulnerable to extreme temperatures, humidity, and variations in power supply [3]. Damage to sensors caused by climate change can result in incorrect measurements, control malfunctions, and suboptimal system functioning. Because sensors and controllers are relatively small and inexpensive, their durability is critical and often overlooked during design, despite their role in

system performance and occupant comfort. These climate-induced variations should be considered in design considerations [7].

Impacts on automation and performance monitoring. As mentioned, failures or degradation in control and monitoring systems can compromise building automation, fault detection, performance tracking, and occupants comfort [3,7]. In the net-zero energy buildings, where precise control and real-time monitoring are essential for maintaining energy balance and air circulation, even minor control failures can result in significant performance losses and safety issues. Climate-driven reliability in electrical and control systems, therefore, pose a risk not only to durability but also to the verification of energy and carbon performance objectives.

5 Service Life, Adaptability, and Resilience

Climate-Induced Changes in Expected Service Life. Increased operating hours, thermal cycling, and high humidity are reducing the service life of building systems. HVAC equipment faces mechanical fatigue from prolonged cooling and frequent cycling, while air-source heat pumps endure stress from extreme temperatures. Solar PV systems are impacted by thermal stress and degradation of components, leading to premature performance decline. These climate-related stresses necessitate climate-adjusted durability assessments to avoid higher life-cycle costs and reduced reliability [4,15].

Adaptability and Retrofit Potential. Adaptability of the building systems to accommodate future changes in climate, use, or technology is a key dimension of resilience. Systems designed with modularity, flexibility, and ease of replacement are better positioned to respond to changing climatic conditions. For example, HVAC systems that allow for capacity expansion, control upgrades, or integration with renewable energy sources can extend functional service life without full system replacement. Retrofitting aging systems to meet higher cooling demands, improve moisture management, or integrate electrification measures can significantly enhance resilience. Durable materials and components that support repeated retrofit interventions without performance loss are therefore critical for long-term sustainability in cold-climate buildings [4,16].

System Robustness under Climate Uncertainty. Climate uncertainty introduces challenges in predicting long-term performance and degradation pathways. Buildings must remain functional under a wide range of future conditions, including unanticipated extremes such as the 2021 heat dome in British Columbia [2]. Robustness, the capacity of systems to maintain acceptable performance despite uncertainty, depends on conservative design margins, durable component selection, and redundancy in critical systems. Hybrid HVAC systems, diversified energy sources, and resilient control strategies can enhance robustness by reducing reliance on single components. However, robustness must be balanced with complexity and affordability, as increased system complexity can introduce additional durability risks if components and controls are not designed for long-term reliability [9,17].

Failure Risk during Extreme Events. Extreme climate events pose acute risks to building systems and occupant safety, the 2021 heat dome revealed the human cost of homes not designed and upgraded for extreme heat [2]. System failures during heat waves, cold snaps, or prolonged power disruptions can have severe consequences, particularly for vulnerable populations. Enhancing durability and climate resilient [18] reduces the likelihood of catastrophic system failures during such events. This includes selecting materials and components with higher tolerance to temperature and moisture extremes, improving system protection and redundancy, and ensuring that maintenance and inspection practices reflect evolving climate risks [9].

6 Maintenance, Inspection, and Replacement Implications

Increased Maintenance Frequency. Higher operating hours, greater thermal variability, and more frequent extreme events contribute to accelerated degradation of HVAC, solar PV, and electrical systems. HVAC equipment experiences increased wear due to prolonged cooling operation and frequent cycling, while solar PV systems are subjected to mechanical and thermal stresses from snow, ice, and growing temperature fluctuations. These conditions necessitate more frequent maintenance interventions, including filter replacement, refrigerant checks, mechanical inspections, and electrical component testing. Failure to adjust maintenance schedules to reflect climate-driven stresses can lead to premature system failures and reduced service life [4,8,16].

Climate-Responsive Inspection and Maintenance Strategies. Traditionally, inspection practices focus on periodic, time-based assessments rather than climate-responsive risk factors. Under evolving climate conditions, inspection regimes must be adapted to account for exposure to heat waves, extreme cold events, moisture intrusion, and thermal cycling. For instance, post-event inspections following extreme heat or heavy snow events can help identify covert damage to HVAC components, solar PV modules/mounting systems, and electrical components. In high-performance buildings, where systems operate closer to design limits, climate-informed inspection protocols would help for identifying early signs of degradation and preventing system-wide failures [4,13].

Ease of Repair and Replacement after Extreme Events. Resilient buildings must be designed with repairability and replaceability in mind. Climate-related damage can necessitate rapid replacement of vulnerable components, such as PV modules, inverters, sensors, or control devices, to restore system functionality. Systems that are modular, accessible, and standardized allow for faster repairs and reduced downtime following extreme events. Conversely, tightly integrated or poorly accessible systems can significantly increase repair costs and prolong service disruptions, undermining the performance goals and systems resilience objectives [4,13].

Life-Cycle Performance under Changing Climate Conditions. Maintenance and replacement decisions play a critical role in determining life-cycle performance and costs.

Climate-induced reductions in service life can increase the frequency of component replacement, affecting both economic and environmental performance. Incorporating climate-adjusted service-life assumptions into maintenance planning and asset management frameworks enables more accurate forecasting of costs, energy performance, and carbon impacts. For net-zero buildings, maintaining system performance over time is essential to ensuring that energy and emissions targets are met throughout the building's operational life [2,4,13,15, 17].

7 Conclusions

Climate change is significantly altering the environmental conditions impacting building systems, especially in cold-climate regions like Canada. As climate variability increases and extreme events become more frequent, traditional design and service-life models are often inadequate. This paper reviews the effects of evolving climate stressors on the durability and performance of HVAC systems, solar PV installations, electrical, and control systems in both new and existing buildings. Findings indicate that durability degradation results from the cumulative impacts of extreme temperatures, thermal cycling, moisture exposure, and operational variability. HVAC systems face heightened mechanical stress from rising cooling demands, while solar PV systems experience issues like thermal cycling-induced microcracking. Moreover, electrical and control systems are critical for overall reliability but are often overlooked. Conventional service-life assumptions now seem unreliable, emphasizing the need for climate-adjusted durability assessments. Buildings that are modular and adaptable are better suited to handle future climate uncertainties. This study highlights the complexity of climate change impacts on building systems, underscoring the necessity for integrated research.

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