

STANDARDS RESEARCH

Climate Change Impacts on Railway Electrification in Canada

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List of Abbreviations

AAR	Association of American Railroads
AC	Alternating Current
AREMA	American Railway Engineering and Maintenance-of-Way Association
BCCAQv2	Bias Correction/Constructed Analogues with Quantile mapping version 2 (statistical downscaling method)
CAPE	Convective Available Potential Energy
CAPEX	Capital Expenditures
CanRCM4-LE	Canadian Regional Climate Model Large Ensemble
CENELEC	European Committee for Electrotechnical Standardization
CF	Correction Factor
CMIP	Coupled Model Intercomparison Project
CN	Canadian National Railway
CSDS	Canadian Sustainability Disclosure Standards
DC	Direct Current
ECCC	Environment and Climate Change Canada
EPS	Electrification Performance Specifications
EN	European Norm
FSL	Fire Season Length
GCM	Global Climate Model
GHG	Greenhouse Gas
GHA	Greater Hamilton Area
GTA	Greater Toronto Area
GWL	Global Warming Level
HV	High Voltage
HVAC	Heating, Ventilation, and Air Conditioning
IDF	Intensity Duration Frequency (curves)
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
LDC	Local Distribution Company
LV	Low Voltage
NRC	National Research Council Canada
OCS	Overhead Catenary System
OPEX	Operating Expenditures
PIEVC	Public Infrastructure Engineering Vulnerability Committee
RCCAP	Rail Climate Change Adaptation Program (Transport Canada)
RCP	Representative Concentration Pathways
REI	Railway Electrification Infrastructure
REM	Réseau Express Métropolitain
RERA	Resilient Railways (recently released)
SSP	Shared Socioeconomic Pathways
TCC	Trackside Control Centres
TCFD	Task Force on Climate-Related Financial Disclosures
TPSS	Traction Power Supply Substation
UIC	International Union of Railways (Union internationale des chemins de fer)

List of Definitions

Resilience: "The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation" [1].

Climate model: "A qualitative or quantitative representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrisations are involved. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal and interannual climate predictions" [1].

Climate projection: "Simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases (GHGs) and aerosols and changes in land use, generally derived using climate models. Climate projections depend on an emission/concentration/radiative forcing scenario, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized" [1].

Coupled Model Intercomparison Project (CMIP): "A climate modelling activity from the World Climate Research Programme (WCRP) which coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. The CMIP3 multi-model data set includes projections using Special Report on Emissions Scenarios (SRES) scenarios. The CMIP5 data set includes projections using the Representative Concentration Pathways (RCP). The CMIP6 phase involves a suite of common model experiments as well as an ensemble of CMIP-endorsed Model Intercomparison Projects (MIPs)" [1].

Downscaling: "A method that derives local- to regional-scale information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods are based on observations and develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on the quality of the downscaled information. The two methods can be combined, for example, applying empirical/statistical downscaling to the output of a regional climate model, consisting of a dynamical downscaling of a global climate model" [1].

Executive Summary

Climate change is intensifying environmental stresses on Canada's transportation infrastructure, and railway electrification infrastructure (REI) systems are no exception. Electrified rail networks rely on complex electrical and structural components that are sensitive to temperature extremes, ice loads, precipitation, flooding, wind, wildfires, permafrost thaw, and lightning. This research assessed how climate change may impact REI in Canada, evaluated the adequacy of existing codes and standards, and identified opportunities to integrate climate resilience into future standardization.

To guide this assessment, the study focused on four core objectives. The first objective was to evaluate current and projected climate change impacts on REI in Canada, including temperature extremes, flooding, severe weather events, permafrost thaw, wildfires, heat domes, and freezing rain, and to identify relevant climatic indices that can support improved infrastructure resilience. The second objective was to analyze the vulnerability of key railway electrification systems, such as traction power supply substations, overhead catenary systems, signaling and communication systems, overhead line structures, grounding and bonding systems, and power supply and distribution to climate-induced stresses, with particular attention to infrastructure and regions in Canada at greatest risk. The third objective was to conduct a comprehensive review of existing standards for railway electrification to assess their adequacy in addressing climate change–related challenges, identify gaps and limitations that may hinder resilience and adaptability. The fourth objective was to develop evidence-based recommendations to update or create new standards that support climate-resilient REI in Canada.

The methodology included a literature review of existing national and international railway electrification standards, climate change impact studies, and climatic indices relevant to infrastructure performance; included an assessment of mid-century climate hazards projected using a Canadian climate dataset and other national sources; and included interviews with interested parties through discussions with utilities, transit agencies, manufacturers, and academia.

The findings revealed that Canada does not yet have a dedicated and current railway electrification standard. Until the new edition of CSA C22.3 No. 8 is released, projects mainly rely on American Railway Engineering and Maintenance-of-Way Association (AREMA), International Electrotechnical Commission (IEC), and European Committee for Electrotechnical Standardization (CENELEC) standards, with CSA C22.3 No. 1 used for climatic loads. These standards depend on historical climate data and rarely include future projections, except for Annex I of CSA C22.3 No. 1:25. A review of vulnerabilities shows that overhead catenary systems are affected by temperature, wind, ice, and wildfires; traction power supply substations by heat, flooding, humidity, and corrosive environments; signals and communication systems by temperature extremes, flooding, wind, lightning, and ice; and grounding and bonding systems by lightning, soil moisture variation, freeze-thaw cycles, and corrosion. For each component, climate indicators, such as one in 50-year wind pressure, one in 50-year ice load, and projected days above 35 °C were proposed to link climate science with engineering design since they represent values used in the design phase for load calculations as an example.

Interviews with interested parties revealed uneven climate adaptation readiness. Utilities reported being more advanced in planning than transit agencies. Transit operators noted that design manuals rarely incorporate climate projections, and manufacturers pointed to limited client demand for climate-resilient equipment and their limited interest in conforming to a new set of design parameters not aligned with European standards.

The research also identified several systemic gaps in existing codes and standards, including continued reliance on historical climate data in design thresholds; absence of climate-specific performance and testing criteria; limited integration of probabilistic or risk-based design methods; insufficient guidance on compound and cascading climate hazards; gaps in addressing secondary climate-driven risks such as slope instability and permafrost degradation; limited regional differentiation in climatic design values; and unclear expectations regarding the scope and depth of climate risk assessments for REI projects. Additional gaps relate to retrofit guidance for legacy systems, the evolving requirements of signaling and communication infrastructure, and the fragmented regulatory landscape for intra-provincial systems.

To address these shortcomings, the research proposes a comprehensive set of recommendations. These include integrating forward-looking climate projections into REI design requirements, developing climate-informed testing protocols for key components, and incorporating risk-based or probabilistic design methodologies aligned with leading international practices. The recommendations also call for clearer guidance on compound hazards, regional exposure classes, and minimum expectations for climate risk assessments, the development of retrofit pathways for existing assets, and the integration of climate considerations into maintenance and inspection programs. Harmonization with relevant IEC, CENELEC, and International Union of Railways (UIC) standards, along with enhanced collaboration among transit agencies, utilities, manufacturers, researchers, and regulators, will be essential to updating Canadian codes and standards.

Overall, this research confirms that Canadian REI is vulnerable to a broad and evolving range of climate hazards, and that current standards do not provide adequate guidance for future conditions. Updating Canadian standards to incorporate projected climate conditions, probabilistic design approaches, and international best practices can strengthen the safety, reliability, and long-term sustainability of electrified rail infrastructure. Embedding climate resilience into codes and standards can help ensure that future REI investments deliver lasting value and remain aligned with national adaptation and decarbonization goals.



"Canada's climate is undergoing significant changes, with an average temperature increase of 2 °C between 1948 and 2023, approximately double the global average pace."

1 Introduction

1.1 National Climate Trends

Canada's climate is undergoing significant changes, with an average temperature increase of 2 °C between 1948 and 2023, approximately double the global average pace [2]. Temperature increases are particularly pronounced in the northern regions, the Prairies, and northern British Columbia during winter, where the annual mean temperature has risen nearly three times faster than the global average [3]. Projections indicate that this trend will persist, with Canada's climate continuing to warm at an accelerated rate, particularly in its northernmost areas [4].

The effects of climate change are far-reaching, extending beyond environmental concerns to affect key aspects of societies such as public health, energy use, economic performance, and infrastructure durability [5]. Impacts vary regionally: accelerated permafrost thaw is a major challenge in the north, while rising sea levels and diminishing sea ice threaten coastal communities and their ecosystems, infrastructure, and essential services through heightened storm surge intensity [6]. Urban areas face increasing frequency and intensity of extreme precipitation events (e.g., urban flooding), heatwaves, and the intensification of the urban heat island effect [6]. Rising air temperatures also increase atmospheric moisture and convective available potential energy (CAPE), both of which are key factors in severe thunderstorm development. These storms, often accompanied by high winds and lightning strikes, pose significant risks to energy transmission networks, stormwater infrastructure, and transportation systems [7].

The transportation sector is a significant contributor to Canada's greenhouse gas (GHG) emissions. In 2022, it was responsible for 196 megatons of CO_2 eq, accounting for 28% of Canada's total emissions [8]. Within this sector, road transportation, including personal vehicles and heavy-duty trucks, contributed 61% [8]. Expanding sustainable transportation modes can reduce average kilometres driven per vehicle and support Canada's broader climate and mobility goals.

Railway emissions accounted for 4% of total transport-sector emissions in 2022, covering both freight and passenger services [8]. Passenger rail contributed approximately 5.4% of railway emissions [9]. To address this, Canada is prioritizing railway electrification as a sustainable alternative to diesel-powered trains, reducing fossil fuel dependence and cutting GHG emissions [8]. For instance, Metrolinx is considering projects to electrify core segments of its commuter rail network in the Greater Toronto Area (GTA) and Greater Hamilton Area (GHA), aiming to introduce electric trains and improve service efficiency [10]. Through the Canada Public Transit Fund, the government plans to invest $3 billion annually starting in 2026–2027 to support sustainable public transit. This funding may include railway electrification projects as part of efforts to modernize and expand transit infrastructure across the country [6].

The Canadian government is also promoting sustainable rail infrastructure through initiatives such as the High Frequency Rail project, which aims to establish modern, resilient, and mostly electrified tracks connecting major cities, including Quebec City, Montreal, Ottawa, and Toronto [11].

1.2 Implications of Climate Change on Railway Electrification Infrastructure (REI)

Canada's railway electrification system faces increasing climate-related risks due to the multifaceted exposure of REI systems. A recent study of potential impacts of climate change on public transit system highlights a number of climate events with significant consequences on operation of the railroad transportation sector [6]. Key examples include:

- **November 2021, British Columbia:** Floods and landslides in British Columbia caused by heavy rains, part of an atmospheric river system covered the rail tracks near Cheam View and Hope leading to train derailment on November 14 [12]. The flooding and landslides resulted in disruptions to the supply chain in British Columbia. This disruption affected the movement of billions of dollars' worth of goods, as the western province serves as Canada's gateway to the Pacific [13]. The Port of Vancouver, which handles a significant portion of Canada's merchandise trade, faced increased congestion due to the halted rail services. In addition, supply shortages resulting from transportation disruptions can contribute to higher prices.
- **July 2024, Jasper, Alberta:** A wildfire spread and damaged close to one third of Jasper in Alberta, causing over $880 million in damages [14]. During this event, the Canadian National Railway (CN) had to suspend operations through the city [15]. In September 2024, CN announced the relocation of its operations 100km away from Jasper to Hinton, in Alberta, due to ongoing wildfire threats. This decision impacted around 200 workers and Jasper's local economy, which relies heavily on rail access and tourism [16]. Jasper's economy is heavily reliant on rail operations and tourism, and the loss of rail operations threatened the town's economic stability and identity, especially in the wake of the recent wildfire devastation [17].
- **Eastern rail system, 2023:** Connecting Nova Scotia to mainland Canada, the system is increasingly vulnerable to flooding and rising sea levels due to climate change [18]. In 2023, a severe Nor'easter—a powerful storm with strong winds and precipitation—caused significant flooding and disrupted rail transportation and the link between the Port of Halifax and the rest of the country [19].

Understanding resilience is critical in this context. The Intergovernmental Panel on Climate Change (IPCC) [20] defines resilience as the capacity of social, environmental, and economic systems to cope with hazardous events or long-term stressors by responding or reorganizing in ways that preserve their core functions, identity, and structure. This definition also emphasizes the importance of maintaining the ability to adapt, learn, and transform over time. Resilience, in this view, overlaps conceptually with vulnerability, adaptive capacity, and risk, and serves as both a system characteristic and a strategic goal in climate adaptation. In practical terms, many adaptation measures are designed around the idea of resilience as the ability to "bounce back" after disruption, though this may also involve transformation when returning to a previous state is not feasible or desirable.

1.3 Objectives of the Research

This research evaluates how climate change could impact REI in Canada. As extreme weather events become more frequent and intense, the electrical systems that support rail operations face increased stress and risk.

The research objectives are fourfold:

1. **Review standards and codes:** Examine existing electrical standards and codes for REI and identify gaps and limitations in addressing resilience and adaptation to climate change.
2. **Assess climate impacts:** Evaluate current and projected impacts of climate change on REI, with particular attention to hazards such as temperature extremes, flooding, strong winds, permafrost thaws, wildfires, polar vortex events, heat domes, and freezing rain. A detailed list of relevant climate indicators is compiled to assess the resilience of the REI systems in the face of these hazards.

3. **Conduct vulnerability assessment:** Analyze key REI systems, including overhead catenary systems (OCS), traction power supply substations (TPSS), signaling and communication, grounding and bonding, and power supply and distribution networks, to determine where standard-based adaptations are most urgently needed.
4. **Develop recommendations:** Provide evidence-based recommendations, informed by input from key interested parties, to guide updates to existing standards or the development of new ones that enhance the climate resilience of REI across Canada.

2 Methods

This research employed a mixed-methods design combining qualitative and quantitative approaches to provide a comprehensive understanding of the climate change impacts and how prevalent standards can be enhanced. The quantitative component focused on analyzing current and projected climate hazards relevant to REI. The analysis drew on available climate projections, technical literature, and engineering criteria to assess potential vulnerabilities.

The qualitative component involved a structured review of existing electrical standards relevant to railway electrification in North America, with a focus on identifying how current standards integrate climate adaptation considerations. Documents were analyzed using a content analysis framework to assess the presence of resilience-related provisions, references to climate data, design thresholds, and adaptation measures. In addition, inputs from key interested parties, including infrastructure owners, operators, and technical experts, were collected through targeted consultations to help ensure this research reflected the emerging needs for integration of climate resiliency in REI industry. The collected inputs informed the identification of key gaps and contextualized the proposed solutions.

The integration of both analytical strands supported the development of evidence-based recommendations that could update or supplement standards in a consistent and practical way.

2.1 Literature Review

A comprehensive analysis of industry codes and standards relevant to the design, maintenance, operation, and quality control of REI systems was conducted to assess how climate resilience considerations are integrated. This involved identifying and examining relevant codes and standards across multiple regions (Canada, the USA, Europe, and other international regions) and across key infrastructure components, including signaling and communication, TPSS, grounding and bonding, and OCS. Each standard was systematically evaluated to determine the extent to which it addresses climate-related risks and incorporates resilience measures.

This review enabled the identification of gaps in current Canadian industry standards regarding climate resilience. To investigate global best practices under environmental conditions similar to those in Canada, standards from the following bodies were assessed:

- **CSA:** Typically applied in Canada to help ensure the quality and safety of products, services, and systems across sectors [21].
- **AREMA (American Railway Engineering and Maintenance-of-Way Association):** Primarily applied in North America, especially in the United States and Canada, providing recommended practices for the design, construction, and maintenance of railway infrastructure [22].
- **CENELEC:** Harmonizes technical standards across European Union member countries in electrical engineering [23].
- **IEC:** These standards are international, covering a wide range of electrical, electronic, and related technologies. They are developed by experts from different countries to facilitate international trade and help ensure that products meet consistent performance and safety criteria worldwide [24].

A summary of the standards reviewed and the REI components they address is provided in Table 1. Of the standards reviewed here, CSA-C22.3 No. 8-M91 is no longer an active standard, as both the 1991 edition and the subsequent 2003 revision have been withdrawn.

In addition, a literature review was conducted of scientific papers, government and academic reports, and sectoral studies focused on the impacts of climate change on electric railway operations and the proposed adaptation measures. Key studies, such as "Implications of climate change for railway infrastructure" [25] and "Analysis of the climatic factors influence on the overhead transmission lines reliability" [26], provided detailed information on the critical climate indicators for each component. Standards and regulatory frameworks from New Zealand, Australia, and Northern Europe were also assessed to identify best practices for regions with comparable environmental conditions.

This research builds on previous CSA studies, including "Climate change resilience and adaptation for public transit" [6] and "Development of climate change adaptation solutions within the framework of the CSA Group Canadian Electrical Code Parts I, II and III" [27]. Reliable Canadian data sources informed the review of evolving climate trends and projected scenarios, such as climatedata.ca [28], "Wildfires and climate change" [29], and "Canada's changing climate report" [30].

Insights from the electricity transmission sector also informed potential next steps for adapting railway electrification standards, as this sector has already implemented significant adaptation measures. Annex I of CSA C22.3 No.1:20, *Overhead Systems,* for example, now provides recommended approaches for adapting to climate change [31].

Beyond technical standards, broader professional guidance on climate change adaptation was considered. The "Engineers Canada model guideline on principles of climate change adaptation for professional engineers" emphasizes integrating adaptation into practice, reviewing the adequacy of current standards, and applying risk-based approaches over the full service life of infrastructure [32]. These principles reinforce the importance of moving beyond reliance on historical climate data and highlight engineers' duty of care to anticipate future climate risks.

Incorporating these guidelines helps ensure that the evaluation of standards aligns with evolving expectations of professional engineering practice in Canada and contextualizes the gaps and opportunities for updating railway electrification standards.

2.2 Key Informant Interviews

To help ensure the completeness, accuracy, and practical relevance of the research findings, 42 representatives from utilities, transit agencies, railway operators, manufacturers, and academia were contacted to participate in key informant interviews (see Table 2 for a breakdown of interested parties interviewed). Of these, 17 participants provided input that was incorporated into the analysis, including 15 external experts and two CIMA+ railway engineers involved in Montreal's Réseau Express Métropolitain (REM) electrified rail transit project.

The main objectives of the interviews were to:

- Establish a deeper understanding of how climate change is integrated into the standards landscape.
- Gather insights on potential opportunities, limitations, challenges, and considerations for updating standards in Canada from the perspective of local operators and manufacturers.
- Identify gaps in climate resilience knowledge and standards with input from national and international climate change experts.

Most of the identified representatives held engineering roles in the design or operations of electric railway systems. Interviews with utilities focused on how they assess climate change impacts and potential adaptations of their distribution infrastructure, including the effect of connecting an electric railway to the grid on overall network resilience.

Interviews and surveys with transit agencies and railway operators explored operational challenges with existing electrified rail infrastructure, particularly limitations in original design parameters that may contribute to extended downtime or increased maintenance under changing climate conditions. Understanding these perspectives is critical as operators transition away from diesel-powered locomotives and consider how existing standards could support or hinder the electrification.

Table 1: REI standards reviewed

Standard	Country/ Region	Publication year	REI component	Reference
CAN/CSA-C22.3 No. 8-M91, Railway Electrification Guidelines [superseded (R2003) and later withdrawn]	Canada	1991/2003	OCS; Signaling and Communication; Grounding and Bonding	[33]
CSA C22.3 No. 60826:19, Overhead transmission lines — Design criteria	Canada	2019	OCS	[34]
CSA C22.3 No. 1:20, Overhead Systems [superseded by No. 1:25]	Canada	2020	Signaling and Communication; Grounding and Bonding	[31]
CSA C22.3 No. 1:25, Overhead Systems [current edition]	Canada	2025	OCS; Signaling and Communication; Grounding and Bonding (with mandatory Canadian Code of Authority requirements introduced in this edition)	[35]
CSA C235:19, Preferred Voltage Levels for AC Systems up to 50 000 V	Canada	2019	TPSS	[36]
Metrolinx DS-05, Sustainable Design Standard	Canada [ON]	2021	TPSS, Signalling and Communication, Grounding and Bonding	[37]
Metrolinx DS-05, Sustainable Design Standard, Rev. 2	Canada [ON]	2025	TPSS, Signalling and Communication, Grounding and Bonding	[38]
AREMA Manual for Railway Engineering	USA	Updated annually	TPSS, Signalling and Communication, Grounding and Bonding	[39]
CENELEC EN 50119:2020, Railway Applications – *Fixed Installations – Electric Traction Overhead Contact Lines*	Europe	2020	OCSs	[40]
CENELEC EN 50123-1:2003, Railway Applications – Fixed Installations – D.C. Switchgear – Part 1: Genera	Europe	2003	TPSS	[41]
CENELEC EN 50123-2:2003, Railway Applications. Fixed Installations. D.C. Switchgear D.C. Circuit Breakers	Europe	2003	TPSS	[42]
CENELEC EN 50123-4:2003/A1:2013 (Amendment), Railway Applications – Fixed Installations – D.C. Switchgear – Part 4: Outdoor d.c. Disconnectors, Switch-Disconnectors and Earthing Switches	Europe	2013	TPSS	[43]
CENELEC EN 50123-6, Railway Applications – Fixed Installations – D.C. Switchgear – Part 6: D.C. Switchgear Assemblies	Europe	2003	TPSS	[44]

Standard	Country/ Region	Publication year	REI component	Reference
CELENEC EN 50124-1, Railway Applications – Insulation Coordination – Part 1: Basic Requirements – Clearances and Creepage Distances for all Electrical and Electronic Equipment	Europe	2017	Grounding and Bonding	[45]
CELENEC EN 50124-2, Railway Applications – Insulation Coordination – Part 2: Overvoltages and Related Protection	Europe	2017	Grounding and Bonding	[46]
CENELEC EN 50125-3:2003, Railway Applications – Fixed Installations – D.C. Switchgear – Part 1: General	Europe	2003	Signals and Communication	[47]
IEC 60721-2-2:2024, Classification of Environmental Conditions – Part 2-2: Environmental Conditions Appearing in Nature – Precipitation and Wind	International	2024	OCS	[48]
IEC 60850:2014, Railway Applications – Supply Voltages of Traction Systems	International	2014	Power, Transmission, and Distribution	[49]
IEC 60913:2024, Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines Systems	International	2024	OCS	[50]
IEC 61936-0:2023, Power Installations Exceeding 1 kV AC and 1,5 kV DC – Part 0: Principles to Be Observed in the Design and Erection of High Voltage Installations – Safety of High Voltage Installations	International	2023	Grounding and Bonding	[51]
IEC 61992-1:2006, Railway Applications – Fixed Installations – DC Switchgear – Part 1: General	International	2006	TPSS	[52]
IEC 61892-4:2019, Mobile and Fixed Offshore Units – Electrical Installations – Part 4: Cables	International	2019	TPSS	[53]
IEC 62305:2025 SER, Protection Against Lightning [includes Parts 1–4:2024]	International	2025	Grounding and Bonding	[54]
IEC 62497-2:2010, Railway Applications – Insulation Coordination – Part 1: Basic Requirements – Clearances and Creepage Distances for All Electrical and Electronic Equipment	International	2010	OCS	[55]
IEC 62498-2:2010, Railway Applications – Environmental Conditions for Equipment – Part 2: Fixed Electrical Installations	International	2010	OCS	[56]

Table 2: Interested parties identified for interviews

Sector	Number of contacted entities	Survey respondents	Participants interviewed
Utilities	6	3	4
Transit agencies	14	6	0
Railway operators	8	0	0
Manufacturers	6	1	1
Academic	8	5	5
Total	**42**	**15**	**10**

Over a three-month period, 25 surveys and interviews were completed with experts across various sectors. Survey findings helped refine the interview topics and questions, ensuring relevance and focus. Insights gathered from participants were integrated into the research as appropriate. The highest levels of participation came from transit agencies, utilities, and the academic sector.

Engaging manufacturers and freight operators proved more challenging, partly because freight operators currently do not use electrified railway infrastructure, given the significant capital costs associated with electrifying long-distance freight transport. Instead, these operators are exploring alternative pathways for decarbonizing their sector.

2.3 Vulnerability Analysis

The vulnerability analysis aimed to provide an overview of the vulnerability of Canada's existing REI to climate hazards. In climate-risk terminology, vulnerability is the degree to which a system or infrastructure is susceptible to or unable to cope with the adverse impacts of climate change, including extreme events, and is a function of both sensitivity and adaptive capacity [32].

- Sensitivity refers to the degree to which a system is affected—either positively or negatively—by climate variability or extremes.
- Adaptive capacity is the ability of a system to adjust, withstand, or recover from the effects of climate hazards, including through design, maintenance practices, and operational flexibility.

In this assessment, the vulnerability of key REI components—OCS, TPSS, signals and communication, grounding and bonding—was evaluated against projected changes in temperature, ice load, lightning flashes, rainfall, and wind. This evaluation was based on system characteristics, operational data, expert judgment, and literature review. However, due to the absence of publicly available information on which standards were used in design, and whether climate-related design variables were adjusted, it was not possible to quantify vulnerability precisely. Instead, the analysis identifies areas potentially more susceptible to projected climate hazards rather than providing a definitive assessment of design robustness.

The analysis focused on projected climate changes under the SSP5-8.5 scenario, a standard global climate outlook representing a "fossil-fuelled development" pathway with high energy use and GHG emissions. SSP refers to Shared Socioeconomic Pathways, and SSP5-8.5 provides a conservative, upper-bound estimate of climate risks, ensuring that recommendations remain robust even if global emission reductions fall short.

A mid-century time horizon (2041–2070) was selected to align with the expected service life of most electrification assets. The baseline period, typically 1991–2020, depends on historical data availability. Core REI components such as OCSs, substations, and switchgear, are designed for service lives of 30–50 years, after which major refurbishments, retrofits or replacements are expected. This timeframe aligns with the capital planning and budgeting cycles used by Canadian transit agencies and Infrastructure Canada. The mid-century horizon also provides projections with lower

uncertainty than end-of-century scenarios (2071–2100), which carry substantially higher projection spreads.

The vulnerability maps were generated using Python scripts applied to the CanDCS-U6 dataset [58]. The CanDCS-U6 uses the BCCAQv2 downscaling method (Bias Correction/Constructed Analogues with Quantile mapping, version 2). This approach corrects coarse-resolution climate model outputs against observed data, then applies quantile mapping to align projected distributions with observations. The method preserves large-scale climate signals while improving local-scale representation [58].

While some REI elements (e.g., foundations and civil works) may remain in service beyond 50 years, the mid-century horizon reflects a balance between the electrical asset service life, capital reinvestment cycles, and the reliability of climate projections. End-of-century scenarios may be considered in future research or regional studies where infrastructure life exceeds 2070, but for national standards development, mid-century projections provide the most actionable balance of robustness and usability.

3 Results

3.1 Global Best Practices and Initiatives

In Canada, all federally funded infrastructure projects must assess GHG emissions and resilience under the Climate Lens framework, aligning with the Greening Government Strategy [59]. National standards development is ongoing, including the CSA D700 initiative [60], which aims to formalize climate adaptation and resilience criteria for transit and passenger rail systems [61]. Transport Canada's Rail Climate Change Adaptation Program (R-CCAP) [62], provides financial support for projects addressing climate-related risks such as flooding, wildfires, and permafrost degradation. Additionally, CSA continues reviewing standards across sectors to enhance the integration of climate change adaptation measures.

Looking internationally, New Zealand stands out for having the most legally enforceable rail-specific framework. Its *Resource Management Act* (1991) and *Zero Carbon Act* (2019) require that all major



infrastructure projects, including rail [61], [64], systematically assess and address climate risks such as flooding and coastal erosion. Through the Tiro Rangi Climate Adaptation Plan and the Rail Plan 2020, the government mandates vulnerability mapping, asset audits, and resilience analyses across rail planning and operations.

Australia lacks a federal rail-specific climate law but benefits from the *Transport Integration Act* (2010) in Victoria [65], which requires adaptation planning for all transport agencies. Nationally, the 2021–2025 Climate Adaptation Strategy and Infrastructure Australia's guidance promote climate data integration and adaptation planning, although implementation remains state-dependent [66].

In Northern Europe, Sweden and Finland demonstrate advanced integration of rail-specific climate adaptation. Since 2017, the Swedish Transport Administration has incorporated climate risk assessments into rail planning [67], guided by national adaptation. Finland's Climate Change Adaptation Plan (2022) explicitly addresses rail resilience, including permafrost impacts in Arctic corridor planning. Norway, while lacking a rail-specific legal framework, mandates climate risk assessments

under its National Transport Plan and collaborates with research institutions to map rail vulnerabilities [68]. Across the Nordic countries, rail agencies also apply the UIC Rail Adapt framework to manage risks such as snow accumulation, landslides, and freeze-thaw cycles [44].

Sweden and Finland demonstrate a well-established integration of legal and operational frameworks for climate-resilient rail systems, while New Zealand stands out among non-European countries for its strong and enforceable regulatory approach. In contrast, Canada and Australia are advancing primarily through planning instruments and financial support programs, though without formalized legal mandates specific to rail [42].

3.2 Components of Railway Electrification Infrastructure (REI)

Electric railways rely on a highly complex integration of multiple systems, each critical to ensuring safe, efficient, and reliable operation. Understanding the function of each component is essential, as failures have different operational consequences. REI comprises several key components that deliver power to trains across the network, and this section highlights these components and their roles.

OCS consists of three main elements designed to deliver electricity to trains through suspended overhead wires, ensuring efficient power supply throughout the journey. The catenary (contact) wires are suspended above the tracks and provide electricity to the pantographs. They are typically made of copper or copper alloy, which is the most widely used material in new designs [70]. The messenger wires primarily support the contact wire ensuring it remains taut and at the appropriate height to maintain consistent power delivery as the train moves. The tensioning equipment is responsible for maintaining the appropriate tension in the catenary wires.

TPSS provides and distributes electrical power to trains. Strategically located along the railway, TPSS converts electrical power from the utility grid into voltages suitable for the railway's power distribution systems (all equipment between the TPSS and train pantographs, e.g., OCS).

Each TPSS typically includes:

- Transformers to convert high-voltage (HV) electricity from the grid to lower voltages (LV) suitable for the railway system.
- Rectifiers in DC systems to convert AC power to DC for train use.
- Switchgear to distribute power to the OCS.
- Circuit breakers to isolate the TPSS in case of faults or overloads.

Typical HV levels in downtown Toronto are 13.8 kV and 27.6 kV, with 44 kV also possible depending on availability. Local distribution companies (LDCs) such as Toronto Hydro-Electric System Limited and Alectra govern these voltages in the GTA. These HV levels are also used elsewhere in Ontario and other provinces and are referenced in CSA C235:19, Preferred Voltage Levels for AC Systems up to 50 000 V [36].

On the LV side, substations typically step down to 25 kV AC for commuter and mainline rail consistent with international guidance (IEC 60850 and IEC 60913:2024) [49], [50]. Urban transit systems—subways, light rail, and streetcars—usually operate at 600–750 V DC, with some newer systems designed for up to 1.5 kV DC, as defined in AREMA and IEC standards. Unlike HV supply, LV levels are set by railway electrification standards and operational requirements.

Signals and communication systems are essential for safe and efficient train operations, preventing collisions. These systems may include Trackside Control Centres (TCC) and wayside signalling equipment.

Grounding and bonding connect electrical equipment and conductive structures to the earth through low-resistance paths. Grounding ensures safe dissipation of electrical energy, maintains a reference voltage (typically zero volts), and protects equipment from lightning strikes. Bonding connects metal components to maintain the same electrical potential, preventing dangerous voltage differences within the system.

While this section focuses on the four components described above, other parts of electrified railway

systems, such as rolling stock, are also vulnerable to climate-related impacts. For example, prolonged heatwaves can increase cooling demands for trains. These elements are beyond the scope of this project.

3.3 Climate Change Impacts on REI and Vulnerability Assessment

3.3.1 Climate-related Design Criteria and Indicators

3.3.1.1 Overhead Catenary System (OCS)

The OCS is one of the most important components of electrified railways. Although currently inactive, CAN/CSA-22.3 No. 8-M91 (R2003) [33] provides specifications for the design of OCS, including supporting structures, such as poles and foundations. The standard also allows the use of other codes/standards, such as those from AREMA, AAR, IEC, and UIC, for systems not explicitly covered [21], [24], [39], [71].

In general, these codes and standards adopt a deterministic approach, using predefined, conservative values, such as maximum expected loads or extreme weather conditions, to ensure safety and compliance via safety factors. These values are typically derived from historical data and represent worst-case scenarios. In contrast, probabilistic approaches determine design values based on a target reliability level for the system or component. This accounts for the likelihood of various loads and environmental conditions, allowing designers to balance safety, performance, and cost by targeting an acceptable probability of failure over the system's life cycle.

Based on reviewed codes and standards, four main weather variables inform OCS design: temperature, wind speed, ice loads, and lightning overvoltage withstand. In CAN/CSA-22.3 No. 8-M91 (R2003) [33], the deterministic ambient temperature without correction ranges from -45 to +40 °C. Design wind speed and ice load reference CSA C22.3 No.1 where the operational wind speed is between 75 and 100 km/hr excluding ice load and without accounting for regional variations [31]. The new Annex I of the standard provides specifications for reliability-based (probabilistic) climatic variables, considering the expected service life of the components.

The AREMA standard, a leading North American specification for fixed point electric and civil railway systems, provides alternative OCS design parameters (Part 4, Section 4.2) [39]. Metrolinx also references AREMA in its Specifications for Electric Traction Enabling Works, requiring OCS structures and foundations to meet AREMA standards [73]. AREMA specifies a maximum conductor operating temperature of 71 to 94 °C [39]. For icing conditions, a radial ice of 12.5 mm, wind speed of 65 km/hr and a minimum temperature of -12 °C are used in OCS design. The design and operating (gust) wind speeds are 77 to 96 km/hr and 96 to 130 km/hr, respectively. Although not explicitly stated in AREMA, wind loading is typically based on short-duration gusts (3–5 seconds), which better represent dynamic forces that can damage conductors, masts, and support structures. CENELC EN 50119:2020 similarly specifies gust winds [40], as in AREMA, for poles under combined ice and wind loads [39].

CENELEC EN 50119:2020 provides additional climate-related design specifications [40]. Minimum temperatures are -20 °C without wind or ice and -5 °C with combined wind and ice effects. Wind, snow and ice loads are based on CENELEC EN 50125-3:2003, with wind speeds classified into four categories (W1–W4) and a maximum of 36 m/s; terrain and height effects are considered [47]. Rainfall is referenced at 6 mm/min, and hailstones up to 15 mm must be considered. Snow and ice loads are categorized from 0 N/m (none) to 15N/m (heavy) and applied consistently across regions.

While CSA C22.3 No. 1:25, Overhead Systems, is not a railway-specific standard, it is widely applied in Canada for railway electrification projects for aspects such as wind and ice loading, clearances, and grounding practices [35]. OCSs share many structural and environmental challenges with utility overhead lines. Earlier CSA railway electrification guidance (e.g., CAN/CSA C22.3 No. 8-M91 (R2003) [33]) directly referenced CSA C22.3 No. 1 for climatic design parameters, making it a de facto reference point until railway-specific standards are fully updated [31].

IEC 60913:2024 provides design and testing guidelines for overhead contact line systems [50], referencing climate-related variables from IEC 62498-2:2010 [56].

Key environmental conditions include:

- **Air temperature and humidity:** up to 100% relative humidity, varying by location (open air, covered areas, and cubicles). Maximum ambient temperatures inside cubicles can be up to +30 K higher than outside.
- **Wind:** reference speeds at 10 m or 500 m heights, based on 10-minute averages and 50-year return periods.
- **Rain and hail:** rainfall intensity of 6 mm/min (IEC 60721-2-2:2024), and hailstones up to 15 mm in diameter considered for equipment design [48].
- **Snow and ice:** accretion loads on conductors categorized into four classes (0–15 N/m) and snow depth requirements for access to cubicles and exposed parts.
- **Solar radiation:** values from 700 W/m² (low) to 1,120 W/m² (high), with up to 10 hours/day exposure.
- **Pollution and particulates:** chemical, biological, and mechanical contaminants (e.g., ballast dust, salt spray) classified into three severity levels.
- **Other hazards:** provisions for lightning (IEC 62497-2:2010), vibrations/shocks near tracks, electromagnetic compatibility, fire protection, tunnel conditions, and seismic impacts [55].

These IEC 62498-2:2010 parameters demonstrate that environmental load cases for REI are internationally codified, though not fully integrated into Canadian standards. Solar radiation and pollution, for example, are not addressed in current Canadian practice except for CSA C22.3 No.1:25, which accounts for solar absorption in ampacity calculations [56].

IEC 62498-2:2010 bases design values on past climate records [56]. With climate change, historical extremes may no longer represent future risks. Forward-looking design for Canadian railway electrification should maintain IEC 62498-2:2010's recurrence interval framework (e.g., 50-year return periods for wind or rainfall) but adjust design values using projected climate data (e.g., CanDCS downscaled datasets, Ouranos projections) [56]. This aligns with emerging Canadian practice, including Metrolinx DS-05, which explicitly require climate-adjusted design values, and CSA PLUS 4013:19 for intensity duration frequency (IDF) curve [37], [81].

Based on North American codes, the following climate indicators for OCS are derived from individual and combined climate variables.

- Temperature range: -45 to +40 °C
- Percentage change in 1:50 year wind pressure
- Percentage change in 1:50 year ice load

Some standards (e.g., AREMA) use a "worst-case scenario" approach, incorporating simultaneous wind, ice, and temperature extremes. CSA C22.3 No.1:25 new Annex I partially addresses this issue, but combined hazard projections for Canada are not yet available [35].

Overall, the performance and longevity of OCS infrastructure are heavily influenced by temperature, wind, and ice loads, underscoring the importance of making explicitly addressing these factors in design standards.

3.3.1.2 Traction Power Supply Substation (TPSS)

The AREMA 2023 Manual for Railway Engineering (MRE) recommends that TPSS designs account for various climatic variables, including maximum and minimum temperatures, maximum ice thickness, 24-hour rainfall, design flood level, maximum and minimum relative humidity, maximum wind speed, altitude above sea level, and the existence of any corrosive atmosphere (air pollution). These variables are included because they directly affect TPSS reliability and safety. Temperature extremes influence cooling and insulation performance; ice and wind loads stress outdoor equipment; and rainfall and flood levels affect water ingress protection. Humidity increases the risk of condensation and flashover; altitude reduces dielectric strength; and corrosive atmospheres accelerate material degradation. Each variable therefore represents a potential pathway for system failure. However, AREMA does not specify numerical design values for these climatic variables. Instead, it refers to IEEE transformer design recommendations, which specify that the allowable winding temperature rise should be less than 65 °C, with the maximum hot-spot winding temperature not exceeding 80 °C.

TPSS design requirements are addressed more explicitly in several CENELEC standards. For example, EN 50123-1:2003 establishes general requirements for



DC switchgear in fixed installations, which are essential for reliable traction power supply [41]. This standard specifies maximum and minimum ambient temperatures of 40 °C and -5 °C, respectively, for indoor equipment installed at altitudes between 120 to 1400 m above sea level. Moreover, relative humidity must be below 50% at a maximum temperature of 40 °C to reduce the risk of condensation-related impacts.

Technical requirements for DC circuit breakers are provided in EN 50123-2:2003 [42], which focuses on performance under short-circuit conditions, operational safety, and fault isolation capability. Circuit breakers are a critical element in protecting the traction power network from overloads and faults. A reference temperature of 35 °C at a single point in time is used as the basis for determining the resistance of circuit-breaker coils [42].

EN 50123-4:2003-4:2003/A1:2013 addresses outdoor DC disconnectors and earthing switches, which are used in traction power networks for maintenance and safety purposes [43]. The specified ambient temperature range for these outdoor devices is 30 °C lower than that for indoor DC switchgear covered by EN 50123-1:2003 [41]. The same temperature-rise limitation also applies to indoor DC assemblies installed in traction substations, as specified in EN 50123-6 [44].

IEC 61992-1:2006 focuses on DC switchgear used in TPSS [52]. It specifies operational temperature ranges from -5 to 40 °C and storage conditions from -25 to 55 °C, while also accounting for altitude, humidity, condensation, and pollution. These provisions aim to ensure reliable operation of DC switchgear across a range of environmental conditions. IEC 61992-4 further applies to outdoor DC disconnectors, switch-disconnectors, and earthing switches used in traction systems [53], emphasizing the need for these devices to withstand elevated temperatures resulting from exposure to sunlight and other environmental factors.

For TPSS more generally, a mean daily temperature of 35 °C is considered indicative of reduced peak transformer efficiency. These standards collectively demonstrate that climatic variables are fundamental to ensuring the safe and reliable design of TPSS, as they directly affect equipment performance, service life, and resilience to extreme environmental conditions.

3.3.1.3 Signals and Communication

For trackside signalling systems, the AREMA 2023 MRE recommends using utility power supply instead of TPSS, which is subject to wide voltage fluctuations [39]. However, AREMA does not provide specific climatic design criteria for signalling and communication systems. Similarly, CAN/CSA-C22.3 No. 8-M91 (R2003) lacks climate-related specifications for these systems [33].

By contrast, EN 50125-3:2003 specifies environmental conditions for signalling and telecommunications equipment using three climatic classes based on geographical regions: T1 (warm temperate, -25 to +40 °C), T2 (cold temperate, -40 to +35 °C), and TX (cold, -55 to +40 °C) [47]. The applicable temperature range also depends on whether the equipment is installed indoors, in shelters, or in cubicles [54]. The standard further specifies ambient relative humidity ranges—15 to 100% for T1, 20 to 100% for T2, and 15 to 100% for TX—and precipitation exposure, requiring equipment to withstand rain rates of 6 mm/min for T1 and T2, and 15 mm/min for TX during a 24-hour event. Wind resistance is specified up to 126 km/hr, and equipment must withstand hailstones up to 15 mm in diameter.

Due to the absence of climate-related specifications in North American norms, this study adopts EN 50125-3:2003 T2 climatic conditions as reference indicators for signals and communication systems [47]:

1. Temperature: Tmin -40 °C to Tmax 35 °C

2. Wind: 1:50 year wind pressure

Here, "1:50 year wind pressure" refers to the design wind load associated with an event that has a 2% probability of occurring in any given year (i.e., once on average every 50 years). Using recurrence intervals in this manner is a standard engineering practice to ensure that equipment can withstand rare but severe wind events over its expected service life.

It is important to distinguish between wind speed and wind pressure. Wind speed refers to the velocity of air movement, typically measured in km/hr or m/s, whereas wind pressure is the force exerted by wind on a surface, expressed in Pascals (Pa) or Newtons per square metre. In engineering design, wind pressure is derived from wind speed using fluid dynamics equations and depends on factors such as air density, surface geometry, and height above ground. For signaling and communication equipment, design specifications often use wind pressure rather than speed, since pressure directly determines the structural load applied to enclosures, antennas, and cabling.

As highlighted in interviews, IEC and EN standards are increasingly adapting to climate change considerations. A notable example is the use of recurrence criteria for wind pressure, which allows transit agencies to incorporate projected future climate change conditions into design requirements. In summary, the reliability of signaling and communication systems is directly linked to their tolerance of climatic stresses, including heat, cold, precipitation, and lightning, highlighting the critical need to integrate environmental variables into signaling and communication system design.

3.3.1.4 Grounding and Bonding

Grounding and bonding systems are essential for all REI components, including OCS structures, wayside equipment, and buildings. While codes and standards generally do not specify climate-related design criteria for these systems, certain climate hazards, such as lightning-induced overvoltage, can directly affect their reliability. This is addressed in AREMA, EN 50124-1:2017, and EN50124-2:2017, which provide guidance on insulation coordination and protection against electrical surges [39], [45], [56].

The IEC 62305:2025 standard provides further guidance on lightning protection for railway systems, and IEC 62305-2 addresses risk management by recommending the selection of an upper tolerable risk limit to define appropriate protection measures [54].

For this REI component, the key climate indicator is the potential increase in lightning flashes due to a warming climate. This metric helps assess how more frequent lightning activity could compromise protective measures and increase the risk of damage to REI systems. Not all lightning events pose the same risk, however: positive cloud-to-ground strikes, though less common, carry higher peak currents and longer durations than negative

strikes, making them more damaging to electrical infrastructure. The magnitude of the current is also critical in determining whether surge protection and grounding systems may be exceeded. While most national datasets report lightning activity as total flash counts—without distinguishing strike polarity or energy—acknowledging these differences underscores the need for designing grounding and bonding systems with sufficient safety margins.

As with other REI components, grounding and bonding systems must account for climatic variables in mind, since variations in soil moisture, freezing conditions, or lightning incidence can compromise their effectiveness and overall system safety.

3.3.2 Projected Climate Change Impacts

3.3.2.1 Temperature Extremes

As discussed in Section 1.1, climate change is increasing the frequency of high-temperature events in Canada. The annual average temperature has risen at roughly twice the global mean rate, with northern regions experiencing even more pronounced warming [30]. This trend has resulted in more frequent and intense heat waves across the country [74].

Higher temperatures affect multiple components of a REI system. For OCS, thermal expansion of conductors increases line sag, which can reduce clearances with other structures and create safety hazards or operational disruptions. Auto-tensioning devices are used in some systems to maintain constant wire tension despite temperature fluctuations. Elevated temperatures also increase electrical resistance, leading to greater power losses during transmission [75]. This reduction in transmission efficiency can result in higher voltage drops along the line for a given traction load, which can affect train performance and may require shorter feeding sections or more frequent substations to maintain acceptable voltage levels [75].

For TPSS, higher ambient temperatures can reduce transformer efficiency and peak operating capacity, while stressing cooling systems and increasing maintenance needs [76]. Oil-based cooling systems can develop "hot spots" around transformer windings. Overheating of transformer cooling fluids has been identified as a major hazard in electrical substations [77].

Signalling and communication components are also sensitive to temperature extremes. Excessive high heat can cause equipment to overheat and fail [25], while cold combined with ice and snow can impair functionality. Low temperatures reduce metal conductivity, which can compromise the effectiveness of grounding and bonding systems in dissipating electrical charges or fault currents.

In Canada, days with maximum temperature above 40 °C are currently rare and projected to remain uncommon. However, days exceeding 35 °C are expected to increase, particularly in southern Alberta, British Columbia, and Saskatchewan. Figure 1 shows the projected change in the number of days with maximum temperatures above 35 °C for 2041 to 2070 under the high emissions SSP5-8.5 scenario, relative to 1991 to 2020. Data are from the CanDCS-U6 dataset [58], which uses statistically downscaled CMIP6 global climate model outputs (with the BCCAQv2 method) to capture local-scale variability. In some regions, extremely hot days may increase by more than 20 per year, which has implications for OCS and TPSS operation, including cooling requirements, thermal expansion, and wildfire risks. Historical incidents, such as the Lytton wildfire and track buckling events, underscore the need for heat-resistant materials, automated tensioning, and improved grounding techniques. Extreme heat can also accelerate. The increased frequency of extremely hot days raises the likelihood of wildfires, which can threaten the safety and operability of entire railway transport corridors.

A study of Canada's electricity system found that transformer capacity remains at 100% up to mean daily temperatures of 33 °C, suggesting that moderate heat increases may not pose immediate concern [76]. Nonetheless, signalling and communication components remain vulnerable to overheating [25].

Cold temperatures present different challenges. Ice accumulation and wind increase mechanical loads on support structures, raising the risk of line failures. Arctic

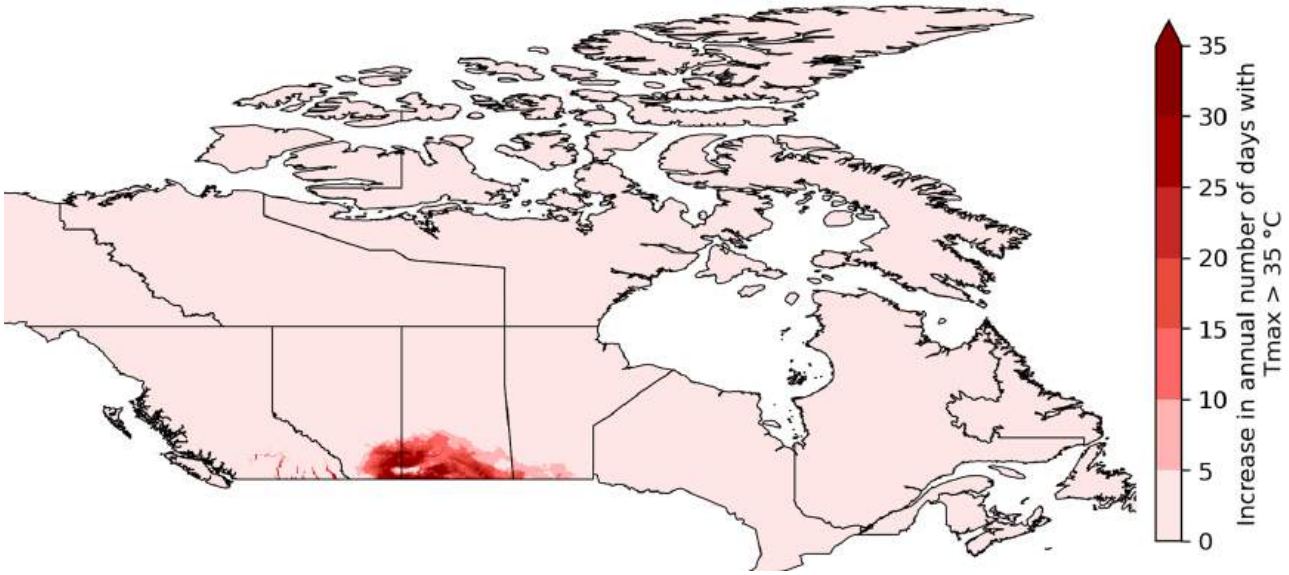


Figure 1: Increase in annual number of days with maximum daily temperature above 35°C in 2041–2070 compared to 1991–2020 period under SSP5-8.5 emission scenario. Dataset: CanDCS-U6 [58].

polar vortex disruptions, which are amplified by accelerated Arctic warming, can produce severe cold snaps, as seen in Texas in February 2024 [78] and central Canada in 2019, where wind chills reached temperatures of -30 to -40°C [6]. Extreme cold affects TPSS performance: transformer oil viscosity increases, reducing cooling efficiency and elevating the risk of overheating under load [79]. Cold conditions can also cause malfunctions in switches and electrical components [80], and ice buildup may freeze switches and impair functionality [27].

Figure 2 map illustrates projected changes in the annual number of days with minimum temperatures below –30 °C across Canada for 2041 to 2070, relative to 1991 to 2020. Northern regions (Yukon, Northwest Territories, Nunavut) are projected to see the largest decreases, exceeding 80 fewer cold days per year. Central Canada (including parts of Manitoba and Saskatchewan) may experience reductions of 48 to 80 days, while southern regions see smaller declines of 12 to 36 days. These spatial trends reflect amplified warming at high latitudes.

Warmer winters bring both benefits and challenges for REI. Reduced extreme cold in southern regions lowers the need for de-icing and snow removal, decreasing maintenance costs. In the north, fewer cold days reduce buildup on overhead catenary lines, lowering the risk of power outages and mechanical failures. However, thawing permafrost in northern areas can compromise track foundations and the structural integrity of poles and overhead lines, introducing new maintenance challenges.

3.3.2.2 Extreme Precipitation

Extreme precipitation is one of the most significant climate hazards affecting REI. Climate change is increasing both the frequency and intensity of extreme rainfall events, thereby elevating flood risks to railway infrastructure. One major concern is pluvial flooding, which occurs when intense rainfall overwhelms local drainage capacity. This type of flooding is particularly problematic in urbanized areas with extensive impervious surfaces, where excessive runoff can lead

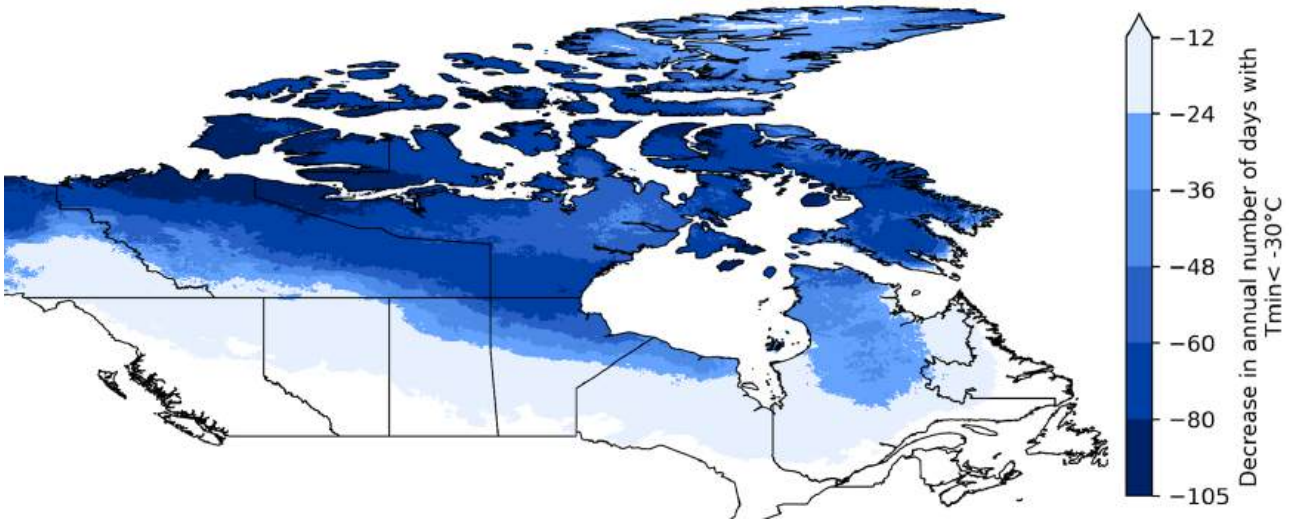


Figure 2: Decrease in annual number of days with daily minimum temperature below -30°C in 2041-2070 compared to 1991-2020 period under SSP5-8.5 emission scenario. Dataset: CanDCS-U6 [58].

to trackside flooding, especially if rail drainage systems are undersized or poorly maintained.

Fluvial flooding presents another major risk and occurs when rivers overflow due to excessive rainfall or rapid snowmelt. Climate change is contributing to milder winters and earlier spring thaws, altering the timing and dynamics of river flooding, particularly in floodplain regions where REI components may be exposed to elevated water levels and erosion. In coastal areas, sea-level rise is reducing the effectiveness of protective structures such as seawalls, increasing the vulnerability of coastal railway infrastructure to storm surges.

Flooding of trackside areas can result in water infiltration and short-circuiting of REI components, leading to service disruptions. Prolonged exposure to moisture can also accelerate corrosion of transformer components manufactured from conventional steel [76]. Under AREMA 2023 MRE, railway drainage systems are typically designed based on the 100-year storm event [39]. However, historical values of 100-year rainfall are increasingly exceeded under projected future climate scenarios [1].

In response, some transit agencies have begun incorporating climate-adjusted design criteria. Metrolinx's DS-05 guideline [37] recommends accounting for climate change impacts by either increasing peak flow estimates by 25% or applying adjusted IDF curves in accordance with CSA Plus 4013:19 for minor storm conveyance systems [71]. For storage and controlled discharge infrastructure, DS-05 advises increasing the 100-year rainfall estimate by 20% and using IDF data based on the RCP 8.5 scenario [37]. Similarly, CSA C22.3 No. 60826:19 recommends that transmission line structures located in flood hazard areas consider the flood elevation associated with a 1-in-50 year event, with additional adjustments to account for climate change [34].

Figure 3 illustrates the change factor for the 1-in-50 year rainfall event for the period 2041 to 2070, relative to the 1991 to 2020 baseline based on temperature scaling using the Clausius-Clapeyron approach. This method assumes that extreme precipitation intensity increases by approximately 7% for every 1 °C rise in temperature and is derived using projections from the CanDCS-U6 dataset [82].

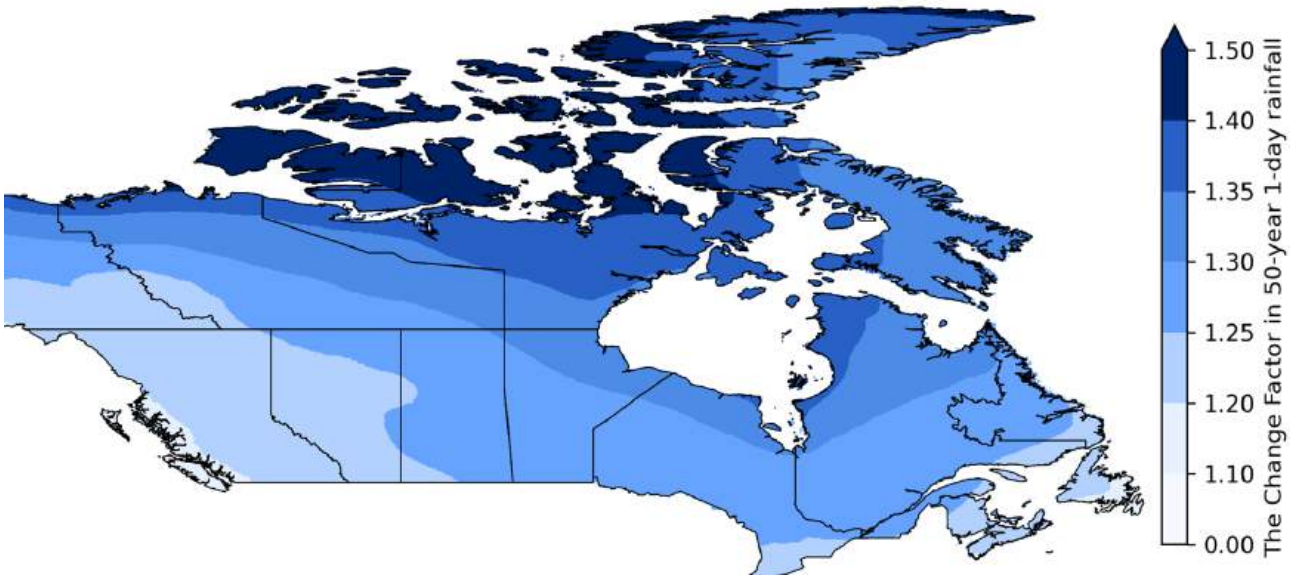


Figure 3: Projected Change Factor for 1:50 year daily rainfall for the 2041–2070 period compared to 1991–2020. Dataset: CanDCS-U6 [58].

The results indicate that northern regions, particularly the territories and northern Quebec, are projected to experience the largest increase in rainfall intensity, with change factors exceeding 1.4 (about 40% increase in extreme precipitation). Central and eastern Canada are expected to see moderate increases, with change factors ranging from 1.2 to 1.35. Parts of British Columbia and the Atlantic provinces show similar projected changes, with some areas approaching or falling below a factor of 1.1.

These projected increases in extreme precipitation have important implications for REI. Heavier rainfall increases the risk of water ingress and damage to substations, signaling, and communication equipment located on the trackside. In addition, saturated soils and increased surface runoff can reduce the effectiveness of grounding and bonding systems, increasing the likelihood of equipment malfunctions and posing safety risks to workers and passengers. Overall, intensified precipitation places additional stress on railway drainage systems, increasing the probability of operational disruptions.

3.3.2.3 Freezing rain and Ice

Freezing rain poses a major climate hazard to OCS by increasing ice loads on contact wires, support structures, and transmission lines, which can lead to mechanical failure [25]. When freezing rain is accompanied by high winds, it can induce conductor galloping, significantly increasing the risk of line damage or collapse [27]. Across the Canadian electrical sector, ice—often combined with snow and wind—has been identified as one of the most severe weather-related threats to infrastructure reliability [27], [76]. Ice accumulation can also freeze electrical switches, impairing the operation of TPSS and disrupting service [27].

The effects of climate change on the intensity and frequency of freezing rain remain uncertain due to the complex meteorological conditions that produce these events and the variability among global climate models and downscaling approaches [83]. While national-scale projections of high-intensity freezing rain events are not yet available, regional studies in Quebec suggest a general decrease in freezing rain frequency in the

southern part of the province and a slight increase in the north [83]. Projections of annual freezing rain hours indicate increases across Alberta, Saskatchewan, Manitoba, northern Quebec, and Ontario, while declines are expected in the Maritime provinces of eastern Canada [83].

Figure 4 presents the projected percentage change in the 1:50 year radial ice load for the period 2034 to 2064 relative to 1986 to 2016, based on CanRCM4 simulations driven by an ensemble of nine CMIP5 global climate models (GCMs) [84]. Radial ice accretion depends on a combination of freezing precipitation rate, wind speed and air temperature [84]. The results indicate that northern and central Canada may experience substantial increases in radial ice loads, up to 200% in some areas, suggesting a growing risk of extreme ice loading on exposed infrastructure, particularly OCS components. In contrast, much of the United States is projected to see decreases of up to a decrease of 100%, reflecting a northward shift in ice storm risk under warming conditions.

Excessive ice loading on catenary wires can cause wire breakage due to increased weight, potentially leading to structural failures and electrical faults. Lessons from past events, such as the 1998 Quebec Ice Storm, highlight the importance of structural reinforcement, ice monitoring, and de-icing strategies. Climate change is altering ice load patterns across Canada, with many major southern cities projected to experience exceeding 20% increase in 50-year ice loads.

3.3.2.4 Permafrost Thaw

Permafrost thaw is a growing concern in northern Canada, where climate change is accelerating warming at a rate higher than the national averages [3]. In some regions, such as the Mackenzie Mountains, permafrost temperatures have increased at approximately three times the rate of air temperature, exacerbating the risk of ground instability [2]. In addition to atmospheric warming, vegetation growth and snow cover also contribute to ground warming and subsequent thawing of the permafrost [84].

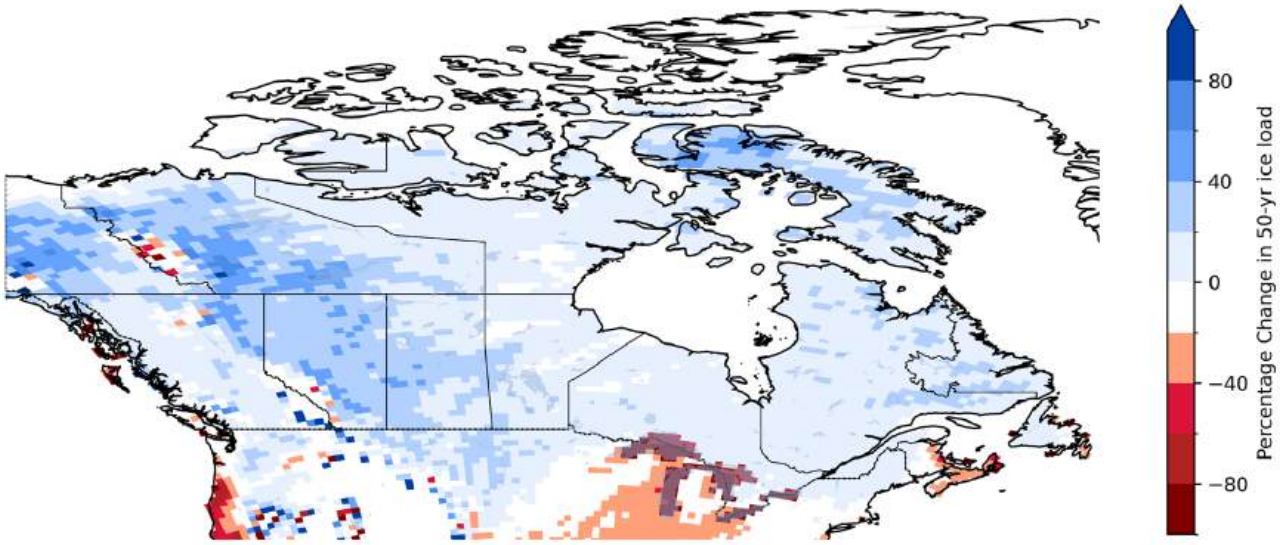


Figure 4: Projected percentage changes in 1:50 year ice load in Canada for the 2034–2064 period compared to 1986–2016. Dataset: [84].

Thawing permafrost results in unstable foundations for rail tracks, transmission lines, and OCS structures, and can damage or destabilize the footings of TPSSs [19]. CSA's technical guidance on infrastructure in permafrost regions recommends continuous monitoring of ground temperature and permafrost conditions over the infrastructure life cycle. It also provides guidance on foundation and methods for evaluating the consequences of foundation system in permafrost environments [84].

Current REI codes and standards primarily focus on foundation design in permafrost areas and do not fully account for future climate-driven thaw. For example, AREMA MRE 2023 recommends designing foundations to avoid disturbing permafrost where possible, or otherwise accounting for the effects of thawing [34]. Similarly, CSA 22.3 No. 60826:19 recommends conducting desktop studies to assess the extent of permafrost thaw impacts on transmission lines and to evaluate associated restoration costs [34]. Assessing climate change impacts on permafrost thaw requires integrating data on ground temperature, land cover, soil ice content, and projected climate variables into thermal models to estimate thaw depth under different climate scenarios.

3.3.2.5 Wildfires

Wildfires are among the most damaging and costly climate hazards affecting railway infrastructure. Climate change is increasing wildfire risk through longer fire seasons driven by extended snow-free periods, higher temperatures, and more frequent hot and dry conditions [20], [58].

Wildfires interact with REI systems in multiple ways. Prolonged dry periods and increased lightning activity elevate ignition risks and can directly damage electrical railway components. Lightning strikes may also trigger fires near electrified corridors, posting a direct threat to infrastructure. While climate change is a key driver of increasing wildfire activity, other factors, including fuel availability, vegetation management practices, and natural or human ignition sources, also contribute [85].

Figure 5 illustrates projected changes in fire season length (FSL) across Canada, defined as the period between the first occurrence of three consecutive days with maximum daily temperatures above 12 °C and the first occurrence of three consecutive days with maximum daily temperatures below 5 °C. The most pronounced increases in FSL, exceeding 40%, are projected in northern Quebec, northern Ontario, and boreal forest zones across central Canada. Southern British Columbia and Alberta are also expected to experience notable increases, though to a lesser extent, increasing wildfire risk near forested railway corridors.

This expansion and northward shift of wildfire-prone zones indicate longer and more intense wildfire seasons, with serious implications for railway operations. Potential impacts include track damage, signal and communication failures, service suspensions, and visibility-related delays [86], [87]. Recent wildfire events, such as those in Fort McMurray (2016), Lytton (2021), northern Quebec and Ontario (2023), and Jasper (2024), demonstrate the vulnerability of railway infrastructure to wildfire hazards. Heat exposure from nearby wildfires can damage cables, signaling equipment, and other electrical components, leading to prolonged service disruptions and increased maintenance demands.

3.3.2.6 High Winds

High winds can significantly affect REI systems, leading to equipment damage such as downed catenary wires, structure failure, and loss of electrical connections [27]. However, the impacts of climate change on high winds remain uncertain as most GCMs lack the resolution needed to accurately simulate localized convective windstorms. A recent study based on CMIP5 GCM simulations [88] projected an increase of 10% to 20% in daily wind gusts events greater than 70 km/hr, suggesting a potential uptick in wind-related disruptions under future climate conditions. For higher-intensity wind gusts (>70 km/hr) increases of 20 to 30% are expected. Older studies based on CMIP3 projections found an increase of less than 6% in extreme wind speeds for south-central and north-western Canada and decrease for the south-western

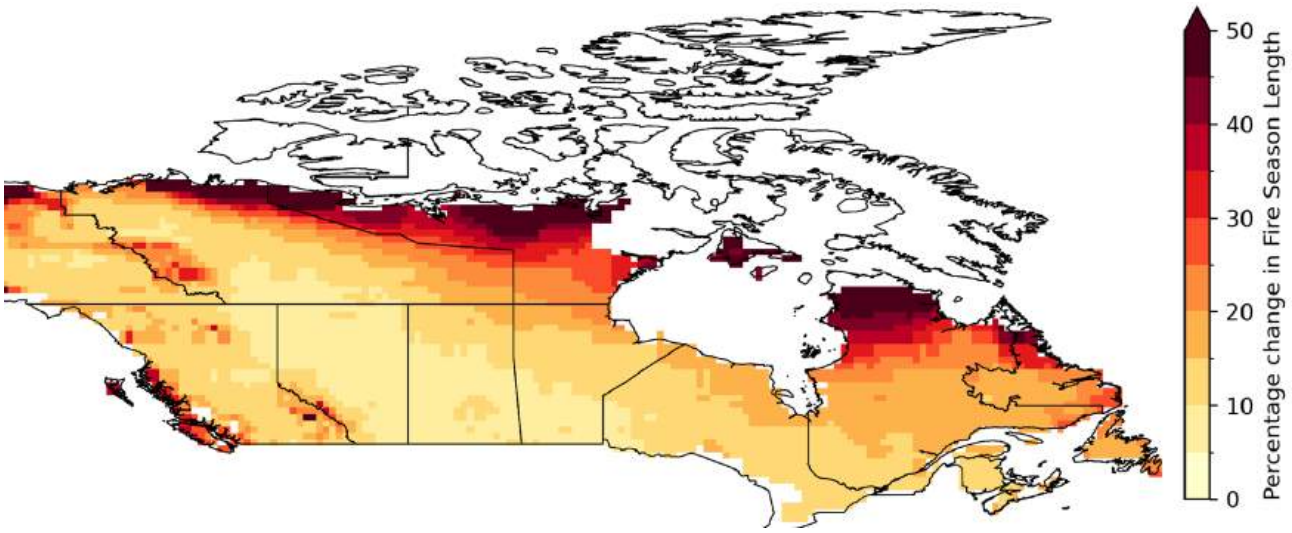


Figure 5: Projected percentage changes in FSL for the 2041–2070 period compared to 1971–2000. Dataset: [85], [86].

and north-eastern Canada [89]. Some standards and specifications provide design guidance for wind loads on REI components. For instance, Metrolinx's for Electric Traction Enabling Works specifications cite a design wind speed of 125 km/hr for OCS support structures [73]. The operating and non-operating (without ice loading) wind speeds in AREMA for OCS system are 77 to 96 km/hr and 96 to 130 km/hr, respectively [39]. Similarly, CSA 22.3 No.60826:19 uses the 1:50 year, 10-minute wind speed at a height of 10 m to calculate dynamic wind pressure on overhead transmission lines [34].

Figure 6 presents the projected changes in 1:50-year wind pressure at 10 m using CanRCM4-LE wind speed simulations with a 20-minutes time step, based on 2 °C global warming levels relative to the 1986 to 2016 period [90]. In practice, converting wind speed into design wind pressure requires a number of adjustments that typically account for the height of the installation, the roughness of the surrounding terrain, the length and flexibility of the span, and, in some cases, the use of longer return periods to capture rarer but more severe wind events.

Figure 6 indicates significant regional increases in extreme wind load, especially in parts of British Columbia, southern Alberta, Ontario, Quebec, and Newfoundland, where wind pressures could rise by 20 to 30%. These increases have critical implications for REI, particularly overhead contact systems and TPSS. Stronger and more frequent wind events elevate the risk of structural stress, wire galloping, detachment, and ice accumulation, which can lead to service interruptions and costly maintenance. To address these risks, OCS structures must be designed for enhanced wind resistance, and more frequent inspections are advised in high-risk areas. For TPSS, elevated wind loads can damage transformers and sensitive equipment, underscoring the need for wind-resistant enclosures and protective systems. These shifts call for strategic design adaptations and resilient infrastructure planning to maintain safe and reliable operations under evolving wind regimes [91].

Designing wind-resistant OCS structures is particularly critical in regions with wind pressure increases of up to 30%, such as southern Alberta and British Columbia. Strong crosswinds can cause OCS wires to oscillate violently (galloping), increasing the risk of wire detachment or snapping. This is especially problematic during winter months, where ice buildup combined with high winds further amplifies oscillations. Conducting routine inspections to identify and address wear or damage caused by wind exposure is essential to ensure the integrity of components.

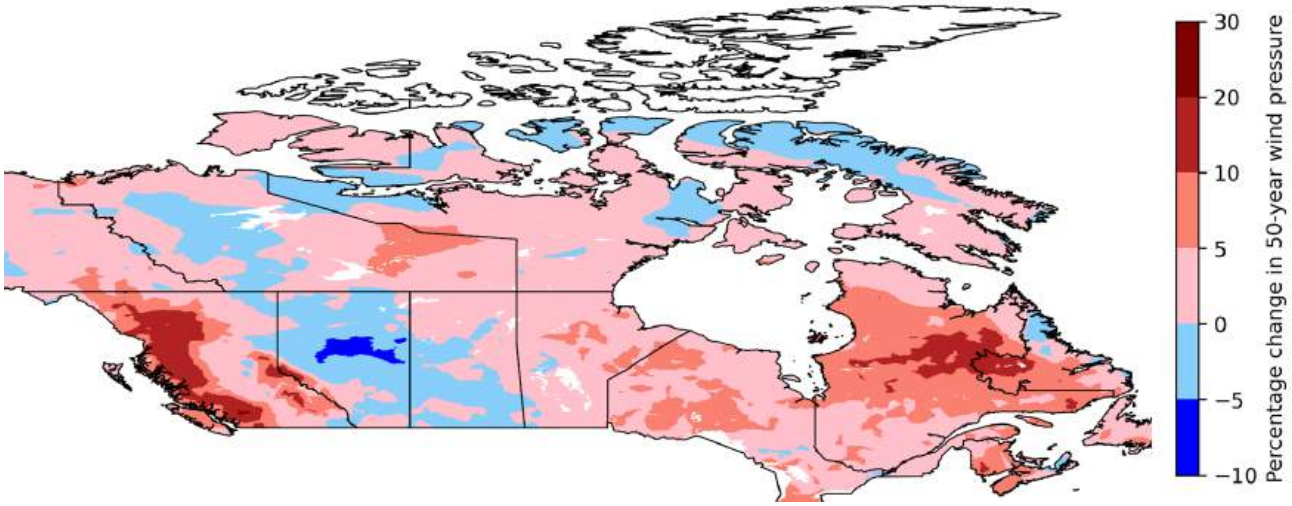


Figure 6: Projected percentage change in 1:50 year wind pressure for 2.0 global warming level relative to 1986–2016 period. Dataset: Design Value Explorer [91].

3.3.2.7 Other Extreme Weather Events

Severe weather events are acute climate hazards that are often seen as low-probability, high consequence events [88]. Thunderstorms, including tornadoes, hail, hurricanes, and lightning, are among the major severe weather events impacting REI systems in Canada. While establishing trends in the frequency or intensity of tornadoes and thunderstorms is difficult, these events are most commonly observed in Prairies, southern Ontario, and Quebec during the summer months (April to September).

Assessing the impacts of climate change on these phenomena is challenging due to the coarse resolution of climate models, which limits their ability to capture the complex atmospheric interactions leading to their formation. However, research indicates that increases in atmospheric instability—described by CAPE—and moisture capacity, both precursors of tornadoes and thunderstorms, are projected to result in more frequent occurrences of these extreme events [92]. Conversely, projects indicate decreases in wind shear (changes in wind speed and direction with height), another precursor, may counteract increases in their formation [93].

As the frequency of thunderstorms increases, so too does the likelihood of lightning strikes. A recent study on the impacts of climate change on lightning activity showed a 12% increase in lightning strikes per degree of warming [76], [94]. Lightning has emerged as a growing climate hazard of concern within the transportation sector [27]. The hurricane season in Canada typically runs from June to November, when Atlantic Ocean temperatures are sufficient to support the formation of tropical cyclones. Climate change is expected to intensify Category 3 to 5 hurricanes and slow their movement, potentially affecting larger land areas [95].

REI codes and standards provide specifications for lightning protection for protection for TPSS and catenary systems, which are vulnerable to overvoltage caused by lightning strikes. For instance, AREMA MRE 2023 recommends installing surge arrestors on OCS, TPSS, and signals and communications equipment to protect against lightning-induced overvoltage [39]. In addition, the use of grounded static wires at the tops of structures and OCS is recommended to ensure the safe dissipation of fault currents to earth. These lightning protection measures are typically designed based on local lightning incidence, as also

specified in Metrolinx's Electrification Performance Specifications EPS-03000 [96]. However, none of these standards explicitly address the projected impacts of climate change on lightning frequency.

Figure 7 presents mean annual lightning flashes across Canada from 1998 to 2023, with the highest concentrations occurring in southern Ontario, particularly the region between Lakes Huron and Erie, which is recognized as a national lightning hot spot. Moderate lightning activity is also observed in southern Manitoba and Saskatchewan [97], where summer thunderstorms are common. Lightning poses serious risks to REI by damaging power lines, transformers, and other electrical systems, often leading to power outages and costly repairs. It is also a primary natural cause of wildfires, especially in boreal regions, where increased lightning activity has been linked to more frequent and severe wildfire events. Rising temperatures may prolong the thunderstorm season, further increasing lightning activity. Climate change compounds these risks, as lightning occurrence is projected to increase by approximately 12% per degree Celsius of global warming [87], amplifying lightning-related hazards on REI.

3.3.3 Vulnerability Assessment

As discussed in Section 2.3, the vulnerability analysis of REI components is based on their sensitivity to specific climate hazards, without explicitly accounting for their adaptive capacity or whether climate change projections were considered in the original design of electrified railway systems. The primary objective of this analysis is to identify regions most affected by each climate hazard relative to the susceptibility of individual REI components, thereby highlighting where potential risks are concentrated under future climate conditions.

Table 3 presents the results of this vulnerability analysis according to the projected changes in climate hazards described in Section 3.1.2. For OCS systems, extreme heat presents a high vulnerability, particularly in southern Alberta and Saskatchewan, due to thermal expansion, conductor sagging in the absence of tensioning systems, and increased exposure to wildfires that can damage poles and wires. Extreme cold presents a medium vulnerability, as materials may become brittle and contract under low temperature; however, cold-related impacts are generally more

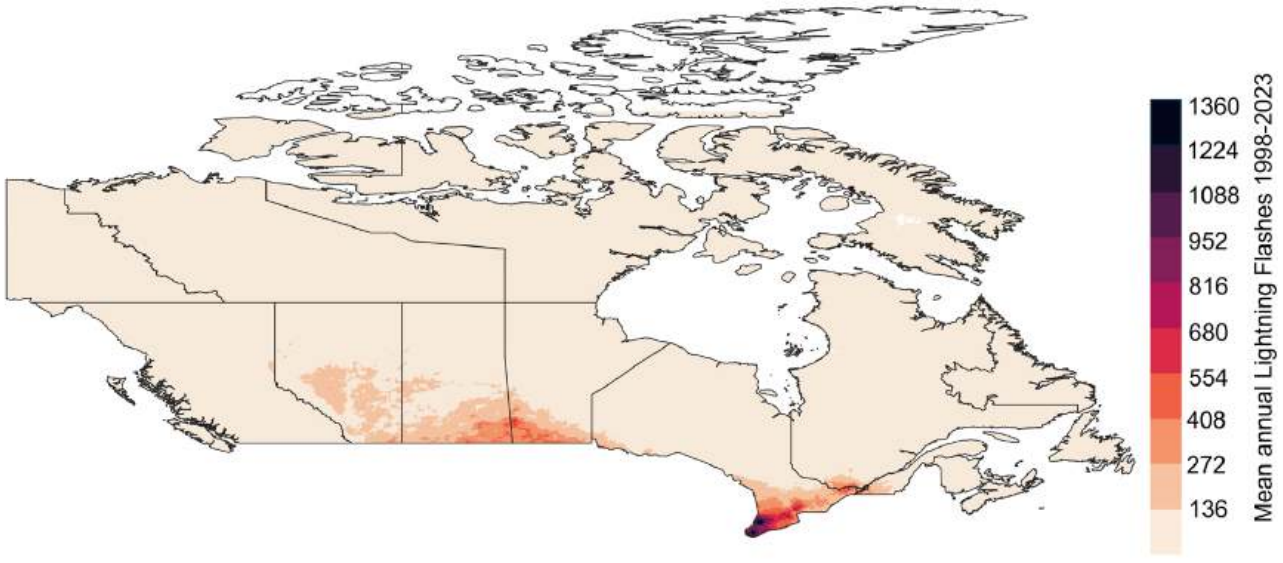


Figure 7: Mean annual lightning flashes for the 1998–2023 period. Dataset: Lightning hotspot maps –Government of Canada [97].

manageable than those associated with extreme heat and are more relevant for northern regions of Canada. Ice and freezing rain are critical threats to OCS, as ice accumulation on wires and structures can result in conductor breakage or structural collapse. Wildfire also presents a high vulnerability for OCS, exposing above-ground infrastructure to direct flames and smoke and increasing the likelihood of damage or service disruption. Lightning presents a medium-level threat, particularly in regions with high flash densities, such as southern Ontario and the Prairie provinces.

For TPSS, the hazards presenting the highest vulnerabilities are extreme precipitation—posing flooding risks across urbanized areas—wildfires, particularly in British Columbia, Alberta, and northern Quebec; and high winds, which are projected to intensify in western British Columbia and may damage substation components such as transformers or enclosures. Signals and communications systems exhibit high vulnerability to ice and freezing rain, lightning, wildfires, and extreme winds, which can damage aerial cabling and sensors, obstruct signal lines of sight, or cause system failures and false readings, thereby disrupting safe railway operations.

For grounding and bonding systems, the most significant climate hazards are extreme precipitation and lightning, both of which can compromise system performance and safety by increasing fault currents or flooding grounding infrastructure. These impacts are particularly concerning given their implications for overall electrical safety and system stability.

Feedback from transit agencies indicated that OCS, substation transformers, and batteries are among the most vulnerable components identified in climate change adaptation planning. Several agencies have already experienced overheating issues, raising concerns about absence of HVAC (Heating, Ventilation, and Air Conditioning) systems in substation designs. Discussions with utility companies suggest that at present no specific vulnerabilities to the broader power grid have been identified due to interconnections with railway power and distribution systems. This is largely attributed to existing protective measures, which are considered sufficient under current operating conditions.

Transit agencies also identified additional pieces of equipment vulnerable to climate hazards that fall outside the scope of this research, including switch clearing devices, switch machines, antennas, overhead cables, and low-mounted power panels. While many component manufacturers have dedicated EcoDesign departments that provide guidance related to climate change, their influence on manufacturing processes and costs remains limited. This is largely because a wide range of equipment options exist within each category, and final design specifications are driven primarily by client requirements. Based on interviewee responses, manufacturers have been adapting by offering equipment with broader operating temperature ranges. However, they noted that materials used in cables are typically not modified for climate adaptation purposes, as clients select cable materials primarily based on electrical and mechanical performance criteria rather than climate resilience.

3.4 Overview of Climate Resilience-Related Gaps in Railway Electrification Codes and Standards

Lack of Requirements for Forward-Looking Climate Data

Most Canadian railway electrification standards rely on historical climate data and static design thresholds, which may no longer reflect future risk profiles. Standards related to REI, particularly those governing the design of OCS, TPSS, and grounding systems, should be revised to incorporate updated climate projections over the expected service life of the infrastructure. For example, adopting projections aligned with high-emission scenarios (e.g., SSP5-8.5) over mid- to long-term horizons (e.g., 2041–2070) or to specific global warming levels such as 1.5, 2 or 3° C, would help ensure infrastructure is designed to withstand future climate extremes rather than historical conditions alone.

Table 3: Vulnerability Matrix for REI with the Region Seeing the Highest Vulnerability

Component	Extreme heat	Extreme cold	Extreme precipitation (IDF)	Ice and freezing rain	Permafrost thaw	Wildfire	Extreme wind	Lightning
OCS	**High** – southern AB/SK (thermal stress, sagging, wildfire)	**Medium** – Central/North (thermal contraction, brittle materials, wire breakage)	**Medium** – countrywide (erosion, washout)	**High** – Central/ Northern Canada (ice load up to +200%, pole strain)	**High** – N. BC, NT (foundation instability, misalignment)	**High** – S. BC, Boreal QC/ON (heat/fire damage to wires, pole collapse)	**High** – BC, S. AB, ON, NL (wire galloping, detachment, pole stress)	**Medium** – S. MB/ SK/ON (pole hits, conductor surge)
TPSS	**Medium** – (cooling needs, equipment stress	**Medium** – (equipment brittleness, insulation cracking, battery backup issues)	**High** – countrywide (flood, infiltration)	**Medium** – Central/North (ice build-up on hardware)	**Medium** – (soil movement, base instability)	**High** – (direct exposure to fire, thermal failure)	**High** – (structure loading, transformer damage)	**High** – Lightning Alley (power surge, transformer failure)
Signals and Communication	**Medium** – (overheating equipment)	**Medium** – (failure, frozen circuits, comms lag)	**High** – countrywide (short-circuiting, water damage)	**Medium** – (ice on cabinets/ poles)	**Medium** – Rail Corridors (alignment failure, comms lag)	**High** – (signal blackouts, melted conduits)	**High** – Wind-prone corridors (antenna damage, relay faults)	**High** – (signal failure, control unit outage)
Grounding and bonding	**Low** – minimal direct effect	**Medium** – (frozen ground increases resistivity, poor grounding efficiency)	**High** – countrywide (saturated soils and flooding, fault risk)	**Medium** – (ice cover affecting contact efficiency)	**Medium** – (permafrost shifts affecting conductors)	**Medium** – (fire-induced disconnection, arcing risk)	**Medium** – (uplift forces on rods and grounding mesh)	**High** – (voltage surges, grounding disruption)

Note: LCD = **AB** = Alberta, **SK** = Saskatchewan, **BC** = British Columbia, **NT** = Northwest Territories, **ON** = Ontario, **NL** = Newfoundland and Labrador, **MB** = Manitoba, **QC** = Quebec

Based on interview findings, half of the transit agencies surveyed have a climate change adaptation plan. However, only half of these plans incorporate climate change considerations into the design of new assets. This suggests that climate change adaptation is a relatively recent priority for transit agencies compared to utilities, all of which had adaptation plans in place. A review of transit agency adaptation plans revealed multiple instances in which specific requirements for the design of new REI systems are absent. One transit agency noted that identifying and integrating minimum climate resilience requirements into design manuals remains a work in progress. Integrating climate resilience into new designs enables adaptation at minimal cost compared with retrofitting infrastructure after construction.

A review of Metrolinx's publicly available climate change adaptation strategy, considered an early effort to integrate climate risk into infrastructure planning, reveals several gaps in applicable design standards. Engineers Canada's Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol was used to assess vulnerabilities and risks across six asset categories [98], leading to the development of the Metrolinx Climate Parameters List. However, this list does not align with the climate variables referenced in key design standards such as CSA, IEC, AREMA, and EN, limiting its applicability to detailed engineering design [21], [24], [39]. Metrolinx also introduced its DS-05, which incorporates climate resilience considerations. However, it provides limited guidance on how design parameters should be adjusted [98]. Notably, DS-05 mandates that capital projects exceeding $50 million undergo a climate risk and vulnerability assessment using the PIEVC methodology [38]. However, because PIEVC is not railway-specific, there is a lack of uniformity in both the depth of analysis and the resulting adaptation measures. The selection and implementation of such measures are also influenced by each transit agency's risk tolerance and the perceived impact on capital costs.

Further review of Metrolinx's design standards, particularly those related to OCSs and other electrical infrastructure, shows continued reliance on AREMA design values, such as radial ice load cases, without climate-adjusted updates [99]. As a result, the degree of climate resilience is largely dependent on the scope and depth of the project-specific risk assessment. In response to current adaptation, some transit agencies have begun adopting updated radial ice load values, as reflected in CSA C22.3 No. 1:20 [31]. However, reliance on formal standards revisions alone may delay urgently needed climate-resilient design changes. Drawing on proactive approaches used by some utilities, transit agencies and governments should take immediate steps to update design parameters to reflect emerging climate risks. One effective approach is the establishment of internal working groups bringing together planning, design, engineering, and asset management teams. Agencies could also form dedicated Climate Change Adaptation committees to guide this process. The ultimate goal is to embed adaptation measures directly into design manuals and decision-making processes, ensuring resilience is integrated into infrastructure independent of formal standards development timelines.

Government and climate policy literature often cite that "every $1 spent on climate change adaptation measures saves up to $15 in terms of the long-term costs involved in mitigating climate change impacts and extreme weather events" [94]. However, there is a perception gap among transit agencies based on the survey results, which often focus on potential increases in both capital (CAPEX) and operational (OPEX) expenditures resulting from more stringent standards. This perspective may reflect an implicit assumption that acceptable service levels remain a matter of agency discretion. While enhanced standards would increase overall infrastructure resilience, transit agencies across Canada and the United States are simultaneously facing financial pressures related to the lingering effects of the COVID-19 pandemic, including sustained levels of remote work that have affected ridership and revenue [101], [102], [103].

Lack of Climate Adaptation-Specific Testing and Performance Criteria

There is a general absence of adaptation-oriented testing protocols, such as evaluating materials under repeated freeze-thaw cycles, prolonged heatwaves, or increased humidity, and no standard process



"There is a general absence of adaptation-oriented testing protocols, such as evaluating materials under repeated freeze-thaw cycles, prolonged heatwaves, or increased humidity, and no standard process exists for assessing REI performance under projected climate conditions."

exists for assessing REI performance under projected climate conditions. In contrast, international practices increasingly include such specifications, particularly for rolling stock and OCS hardware. A recent UIC RailAdapt report, developed in collaboration with international rail operators, recommends testing and operational readiness assessments under conditions such as extreme heat, freeze-thaw cycles, and storm surges [69]. It also promotes climate vulnerability screening during procurement and design. While the RailAdapt framework provides valuable guidance, it remains voluntary and has not been formally adopted in Canada. As a result, Canadian standards and regulatory frameworks lack a coordinated national approach to assessing and addressing climate vulnerabilities across railway electrification systems. UIC has since released the Resilient Railways (RERA) guidance, extending the RailAdapt approach to flooding and heatwaves [72].

Swedish practice includes explicit requirements for testing electrification infrastructure and rolling stock across wide temperature ranges, with specific guidance on freeze-thaw durability, heavy snow loading, and wind drift resilience [104]. No comparable requirement currently exists in Canada to adopt UIC or equivalent international guidance.

Limited Integration of Risk-Based or Probabilistic Design Methods

Standards such as CAN/CSA-C22.3 No. 8-M91 (2003) continue to rely heavily on deterministic values, with limited incorporation of risk-based design approaches that explicitly account for uncertainty, variability, and changing hazard frequencies, approaches increasingly recommended in climate-resilient infrastructure planning [33]. By contrast, international standards (e.g., CENELEC EN 50119:2020 or IEC 60913) have begun incorporating reliability-based approaches and scenario ranges, which are largely absent in Canadian practice (e.g., wind speed or ice load), while compound hazards (e.g., simultaneous high-wind and ice, or wildfire smoke and extreme heat) are rarely considered [40], [50]. Similarly, interdependence between electrification systems and external networks, such as power grids or communication systems, is generally not formally addressed, posing risks of cascading failures under climate stress; however, interviews with utilities indicated that these interdependencies are not currently perceived as a grid-level risk.

The interdependence between REI components and external systems should be addressed in updated standards. This systemic perspective is particularly important for grounding and bonding, where failures can lead to cascading effects across the broader network. Standards updates should encourage or require multidisciplinary risk analysis to address infrastructure interconnections and their vulnerabilities to climate stressors.

Interviews also indicated that, having addressed most significant risks, utilities are now focusing on secondary risks such as landslides, floods, avalanches, slope stability, and ice accretion.

These often result from climate-driven changes in precipitation patterns, snowmelt timing, permafrost thaw, or extreme weather variability. These risks are considered "secondary" not because they are less important, but because they emerge from primary climate drivers and often require more complex, site-specific assessments (e.g., geotechnical or hydrological evaluations). Since this is a relatively recent field of study, such risks are often not addressed in standards. Beyond the scope of this research, knowledge gaps remain, hindering their integration into actionable recommendations. For instance, one interviewee noted that more accurate projections of icing clouds and future wind and ice conditions would be valuable for informing design practices.

Gaps in Signaling and Communication Standards for Climate-Resilient Rail Infrastructure

Informant responses highlighted the limited scope of CSA and AREMA standards around signaling and communications. This sector is evolving rapidly, and existing standards could become obsolete within 10 to 15 years as the European Train Control System Level 2 (ETCS L2) is deployed. Two options are possible: develop standards from scratch or follow European leadership.

Introducing Climate-Specific Risk Assessment Requirements

Standards should explicitly require the evaluation of climate risks during planning, design, and maintenance phases. This includes the assessment of compound climate hazards (e.g., simultaneous exposure to extreme temperatures, wind, and ice) that could affect REI component performance. Guidance on how to apply probabilistic design criteria or reliability-based methodologies should be incorporated to reflect the changing frequency and intensity of extreme events. For example, updates to CSA C22.3 No. 1:20 standards could define new climatic load combinations and return periods reflective of projected risks [31].

The lack of clear framework for addressing climate change in railway electrification results in a situation where clients largely drive market demand, yet many have not fully matured in climate change strategies. This creates challenges for adapting REI across Canada. A more nuanced and location-specific approach is needed. Therefore, updated standards and a consistent climate change resiliency assessment framework are required to reduce variability in requirements while increasing resiliency—or at least ensuring accurate assessment of specific designs.

Limited Reflection of Regional Climate Diversity

Canada's vast geography means that regional climate risks vary significantly, from permafrost thaw in the North to high precipitation in coastal areas. Existing standards offer limited regional differentiation in design thresholds or resilience requirements, potentially resulting in under- or over-designed systems depending on location.

3.5 Climate Resilience Recommendations Complementary to the Codes/Standards

Develop Guidance for Climate-Resilient Retrofit of Legacy Systems

Many Canadian REI assets were designed under historical climate conditions and may not be resilient to future extremes. New standards or technical annexes should provide retrofit guidelines for legacy systems to withstand projected climate impacts. These may include reinforcing OCS poles to resist higher wind loads, improve temperature and humidity control in TPSS enclosures, and upgrade drainage infrastructure to cope with higher precipitation intensity. In addition, standards should allow for phased retrofits to avoid excessive costs, as recommended by interviewees.

Include Informative Annexes for Climate Adaptation Best Practices

Standards could include informative annexes to support practical implementation without imposing overly prescriptive requirements. These annexes may include region-specific climate indicators, sources of climate projection data (e.g., ClimateData.ca), examples of adaptation strategies, and tools for evaluating asset vulnerability. This approach enhances usability while leaving room for context-sensitive engineering judgment.



A best-practice guide could be developed through potential collaboration among federal departments, technical experts, and relevant standards organizations to outline measures such as anti-cascade structures for segmenting OCS lines and targeted risk-based upgrades for vulnerable sections. Such a guide could also include pre-engineering assessment approaches to support rapid response in the event of a failure.

Standards should require that climate-related design parameters for REI (temperatures, wind, precipitation, icing, lightning, etc.) be derived from climate change-informed datasets, using a consistent scenario and time horizon rather than relying only on historical statistics. Climate risk assessments and design checks should explicitly consider relevant compound events, such as concurrent heat and wildfire smoke, wind and ice loading, or pluvial flooding coinciding with high groundwater, using methods adapted from PIEVC. Annexes should include a list of "typical compound hazards" for REI and require at least a qualitative assessment of each. They should also encourage coordination between the REI standard and existing drainage, geotechnical, and structural standards to capture potential multi-system failures.

Best practices could include a national "REI climate exposure map", derived from ClimateData.ca and Environment and Climate Change Canada (ECCC) datasets. For each exposure class, the annex could provide a table of typical hazards and recommended design adaptations. Standards should recommend that owners and regulators integrate climate resilience criteria into project appraisal, procurement, and funding decisions, including life-cycle costing of adaptation measures and inclusion of resilience requirements in contracts. Life-cycle cost–benefit assessments should account for avoided service disruptions and damage when selecting adaptation measures.

Climate Adaptation-specific Testing and Performance Criteria

Standards should require that new projects incorporate climate-informed testing and stress tests for key REI components (e.g., OCS fittings, insulators, signaling cabinets, power electronics) under projected extreme temperatures, ice accretion, flood depths, and wind speeds.

Embed Life cycle Adaptation Considerations in Maintenance and Inspection Protocols

Given the long design life of REI infrastructure, standards should include provisions for adaptive maintenance and inspection responding to evolving climate stress. For example, OCS tensioning systems may require more frequent calibration under increased thermal variability, and TPSS components may require

additional inspection in response to wildfire exposure or air pollution. Embedding adaptive capacity through performance monitoring, redundancy, and planned interventions can enhance long-term service reliability.

Lightning Resilience Under Changing Conditions

Standards should promote the explicit consideration of increasing lightning risk in grounding, bonding, and surge protection requirements for REI, aligning with IEC 61936-1 and IEC 62305 [51], [54], with risk assessments accounting for projected changes in lightning activity over the asset life cycle.

Promote Harmonization with International Best Practices

Where applicable, Canadian standards should align with international norms ,such as those developed by CENELEC and IEC, particularly where they incorporate climate adaptation considerations. For instance, CENELEC's tiered wind and ice classifications and IEC's evolving guidance on component resilience under environmental stressors provide adaptable models for Canadian application. Harmonization ensures consistency for international rail operators and suppliers and encourages adoption of climate-informed design globally.

Future Canadian signaling and telecommunications standards should harmonize with EN 50125-3:2003 environmental classes but updated with region-specific, climate-informed conditions, including temperature, humidity, moisture, and lightning, for Canadian corridors [47].

Considering the Financial Implications of Standard Updates

Recommendations to modify standards should be submitted to a technical committee for review to assess potential cost impacts and prevent excessive financial burden, as suggested by interviewees. Transit agencies reported that they do not currently account for increased costs of new development due to climate change in their financial planning [105]. This type of risk could be captured in a climate-related risk assessment, e.g., under the Taskforce on Climate-related Financial Disclosure (TCFD), and integrated into the Canadian Sustainability Disclosure Standards (CSDS) number 2 on climate-related disclosures [105], [106]. These scenarios represent a transition risk, where policies mandating increased resiliency in new designs could significantly affect project business cases. Therefore, it is important to allocate sufficient resources to model the financial implications of updated standards on new infrastructure, in collaboration with the financial planning teams of transit agencies.

Cross-expertise Collaboration

Updating codes and standards requires collaboration among experts from diverse disciplines. A committee of experts from transit agencies, manufacturers, engineering firms, and federal departments (e.g., National Research Council (NRC), ECCC) could be convened to support the integration of climate change considerations into railway electrification standards. Interview feedback suggests that introducing new standards or codes through a phased approach would help ensure manageable compliance.

Regulatory Gaps in Interprovincial Railway Systems

Notable regulatory gaps exist for intra-provincial rail systems, which are subject to varying provincial rules, while most federal regulations primarily apply to railways operating across multiple provinces (see Table 4). This fragmented regulatory landscape can hinder consistent application of climate adaptation and resilience measures. Addressing this gap will require enhanced coordination between federal and provincial authorities to ensure comprehensive oversight and standardized requirements, including a clear description of the expected climate risk assessment detail. CSA could provide guidance on minimum scope for assessments, such as asset inventory, climate scenarios, hazard screening, components, design variables, risk matrix, adaptation options. Smaller projects may use a simplified screening checklist, while major electrification projects should conduct full quantitative assessments.

Table 4: Identified climate resilience gaps and corresponding recommendations for REI

Identified Gap	Corresponding Recommendations
Lack of requirements for forward-looking climate data	Standards should require the use of climate projection datasets (e.g., ClimateData.ca, ECCC) for selecting temperature, wind, icing, and precipitation design values, rather than relying solely on historical statistics. A CSA informative annex could provide guidance on appropriate scenarios, global warming levels, time horizons, and data sources to ensure consistent application across jurisdictions.
Limited integration of climate-resilient design parameters in adaptation plans and transit agencies manuals	Standards should outline a minimum set of climate-related design parameters for incorporation into their internal design manuals. Periodic updates should be encouraged as codes evolve. Agencies may also benefit from internal climate adaptation working groups to support this integration.
Unclear requirements for the level of detail expected in climate risk assessments	Standards should define the minimum scope and level of detail expected in climate risk assessments for REI. Guidance should link climate hazards directly to design parameters used in AREMA, CSA, IEC, and EN standards for specific component, improving the quality of climate risk assessments conducted using Climate Lens or PIEVC methodologies.
Continued reliance on AREMA design values that do not incorporate climate-adjusted updates	Harmonize Canadian standards with international codes that incorporate climate-informed and probabilistic design methods. Provide guidance on adjusting AREMA design values using updated Canadian climatic projections to support a consistent transition from historical load cases to values reflecting future conditions.
Perceived increases in CAPEX and OPEX due to higher resilience requirements	Incorporate life-cycle costing and benefit assessments that account for avoided damages and service disruptions. Publish guidance on integrating these considerations into planning, procurement, and funding decisions.
Absence of climate-specific testing and performance criteria for REI components	Include climate-informed testing requirements for key components (insulators, OCS fittings, power electronics), covering freeze-thaw cycles, extreme temperature performance, humidity exposure, ice accretion, and wind loading.
Limited use of probabilistic or risk-based design approaches in CSA REI standards	Incorporate reliability-based or probabilistic methods into Canadian REI standards to better reflect the range of plausible future conditions, using IEC 60913 and CENELEC EN 50119 as reference models.
Gaps related to secondary climate-driven hazards (landslides, avalanches, slope stability, permafrost degradation)	Updated standards should acknowledge these emerging risks and provide basic screening guidance. Reference NRC or ECCC datasets and encourage geotechnical or hydrological assessments in high-risk areas.
Gaps in signaling and communication standards, particularly with ETCS-level systems	Future standardization should align environmental requirements for signaling and communication systems with EN 50125-3, adapting thresholds for Canadian corridors. A dedicated working group may be warranted as the sector evolves.
Lack of explicit climate risk assessment requirements within REI standards	Standards should explicitly require climate-risk evaluations during planning, design, and major rehabilitation.
Limited consideration of Canada's regional climate variability	Develop a national "REI climate exposure map" normalize the selection of climatic design values across regions. Pair exposure classes with typical hazards and recommended design adaptations.
Absence of technical guidance for retrofitting legacy REI infrastructure	Provide guidance on practical retrofit strategies, including reinforcement of OCS structures, improved TPSS ventilation and environmental controls, and drainage upgrades. Phased retrofits would mitigate cost impacts.

Identified Gap	Corresponding Recommendations
Insufficient integration of climate adaptation into maintenance and inspection practices	Require adaptive maintenance strategies responding to evolving climatic stressors, such as more frequent tensioning checks for OCS or targeted inspections following heat events or wildfire smoke episodes. Increase performance monitoring to support long-term asset reliability.
Limited harmonization with international climate-resilient standards	Where appropriate, Canadian standards should draw from international practices in CENELEC, IEC, and UIC guidance, particularly regarding climate exposure classes and component qualification under extreme environmental conditions.
No structured assessment of the financial implications of updated climate standards	Before implementing new requirements, technical committees should undertake structured assessments of cost impacts. Collaboration with transit agency finance teams would help quantify transition risks consistent with CSDS-2 climate-related disclosure expectations.
Need for enhanced cross-disciplinary collaboration in standards development	Convene a multi-stakeholder committee including transit agencies, manufacturers, engineering firms, and federal science organizations (NRC, ECCC) to integrate climate science into REI standards. A phased approach would support feasibility.
Regulatory gap for intra-provincial rail systems not covered by federal regulation	Standards should define a minimum expected scope for climate risk assessments across all rail systems, regardless of jurisdiction, clarifying when simplified screening versus comprehensive quantitative assessments is appropriate.

4 Conclusions

This research assessed the climate resilience of Canada's REI through a structured, multi-phase approach. A total of 35 national and international technical norms and standards were reviewed, along with publicly available documents on climate adaptation from other jurisdictions including Sweden, Finland, and New Zealand. The review focused on identifying climate-related parameters for each REI component, selecting climate indicators to evaluate vulnerability in a changing climate, pinpointing gaps in existing codes and standards, and extracting best practices from leading international examples where climate adaptation has been effectively integrated into rail planning, design, and regulatory frameworks.

A Canada-wide vulnerability analysis was conducted to assess how extreme temperatures, flooding, severe weather events (thunderstorms and tornadoes), freezing rain, wildfires, permafrost thaw, and extreme wind could affect REI functionality. The analysis revealed varying levels of vulnerability, highlighting which components are most at risk for each climate hazard across different regions of Canada.

Interviews with REI owners, designers, manufacturers, and operators were central to incorporating practical perspectives. Consultations with transit agencies, utilities, manufacturers, and academics provided critical insights into the limitations of current standards and informed several categories of recommendations for integrating climate resilience into REI standardization. These recommendations include updating codes with forward-looking climate data, adopting risk-based (probabilistic) design approaches, revising thresholds for temperature, wind, and ice loads, incorporating adaptation-specific performance testing to ensure REI functionality, and providing adaptation best practices without prescriptive guidance to support flexible integration into projects.

Participants also stressed the importance of cross-sector collaboration and learning from prior efforts, such as the integration of climate resilience into standards like the Canadian Highway Bridge Design Code. Internal governance mechanisms, including adaptation committees or working groups, were identified as key tools to ensure consistent, informed decision-making when embedding climate resilience into standards and codes.

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Appendix A: Gap → Recommendation Matrix

Abbreviations used in this table are defined in the List of Abbreviations. Standards referenced in this table are cited in the main body of the report and included in the reference list.

Table A-1: Mapping of Identified Gaps in the Research and Corresponding Recommendations for Standardization

Gap in current standards	**Standards based recommendation** (what to add/update in codes/standards)
Reliance on historical climate data; lack of forward looking design values in railway electrification standards (OCS, TPSS, grounding, signaling).	**Mandate climate adjusted design values** using Canadian downscaled projections (e.g., CanDCS U6), aligned to asset service life (e.g., 2041–2070) and appropriate scenarios (SSP5 8.5). Require updated IDF curves (CSA PLUS 4013) and recurrence criteria (e.g., 1:50 wind, rainfall) adjusted for future conditions; include normative references to national datasets.
Absence of adaptation specific testing/ performance criteria (e.g., freeze-thaw, extreme heat/humidity, icing, dust/smoke).	**Create normative test protocols** for REI components (OCS hardware, TPSS switchgear/transformers, signal cabinets) covering heatwaves, freeze-thaw cycles, condensation/humidity, icing accretion and wildfire smoke particulate exposure. Reference ranges based on IEC 62498 2/EN 50125 climatic classes and expand to climate adjusted severity.
Limited use of probabilistic/ risk based design methods (continued deterministic values).	**Formalize reliability based design** (target reliability indices, return periods and load combinations) in CSA C22.3 railway electrification suites; adopt annexes like CSA C22.3 No.1 Annex I across railway applications (OCS poles/foundations, clearances). Provide procedures to select return periods consistent with asset life and risk tolerance.
Insufficient guidance on compound and cascading hazards (e.g., simultaneous wind+ice, heat+wildfire smoke; dependencies with grid/comms).	**Introduce compound hazard design criteria:** define load case combinations (e.g., gust wind + radial ice + low temp) and operational scenarios (smoke/PM affecting ventilation and cooling). Require interdependency analysis (power grid, communications) and protective design to prevent cascade failures (e.g., isolation/ segmentation, redundancy).
Limited regional differentiation despite Canada's climate diversity (permafrost North; coastal flooding; Prairie heat/wind).	**Provide region specific climatic thresholds/annexes:** publish Canadian climatic classes/maps (wind pressure CFs, ice load deltas, extreme heat days, wildfire season length, permafrost considerations) with binding ranges by region and guidance to select design sets for projects.
Lack of standardized retrofit guidance for legacy systems designed to historical climates.	**Publish a retrofit standard/technical specification:** prioritization matrices; reinforcement of OCS structures (wind/ice), TPSS cooling and water ingress mitigation, drainage upgrades for higher IDF, grounding improvements (soil moisture variability). Include phased implementation pathways to manage CAPEX/OPEX.
Signaling and communications climate resilience gaps (North American specs lack explicit climate classes/ limits compared to EN 50125).	**Adopt/align climate classes for signaling** (temperature, humidity, rain, hail, wind) in CSA/AREMA signaling standards; require climate adjusted wind pressure and lightning protection (surge arresters, bonding) with performance verified under future climate loads.
No explicit requirement for climate specific risk assessment in planning/ design (piecemeal agency approaches).	**Make climate risk/vulnerability assessment a normative step** in project design (method neutral but minimum content defined) cover hazards, exposure, sensitivity, adaptive capacity, and mitigation measures; tie outputs to mandatory design value adjustments and documentation.

Gap in current standards	Standards based recommendation (what to add/update in codes/standards)
Knowledge/data gaps (e.g., icing cloud projections; limited compound hazard datasets; lightning polarity/ energy not captured).	**Create informative annexes and data guidance:** specify accepted datasets, uncertainty handling, and conservative adjustment factors where data are incomplete; encourage iterative updates as national datasets evolve (ECCC/Pacific Climate Impacts Consortium).
Financial/implementation barriers (agencies don't budget for climate adjustments; transition risk under CSDS/TCFD).	**Require cost impact assessment within standards change process** (technical committee review of CAPEX/OPEX), reference CSDS/TCFD for disclosure; include staged compliance dates and alternative compliance paths (performance based) to manage affordability.
Regulatory fragmentation for intra provincial rail systems (federal rules largely for interprovincial rail).	**Publish a cross jurisdictional coordination annex:** recommend minimum climate resilience requirements for intra provincial systems and interoperability alignment; encourage provincial adoption or citation in procurement/permits.
Lack of life cycle adaptation in maintenance/inspection (standards focused on design, less on in service adaptation).	**Embed adaptive Operations and Management requirements:** climate triggered inspection frequencies (e.g., after extreme wind/heat events), OCS re tensioning calibration schedules, TPSS cooling/filtration checks during wildfire season; include condition monitoring and thresholds.
Insufficient harmonization with evolving international practices (IEC/ CENELEC integrating environment classes; Canadian practice lagging).	**Map and incorporate international clauses** (IEC 60913, IEC 62498 2, EN 50119/50125) with Canadian deviations to reflect local climate; maintain liaison and periodic harmonization cycles in CSA program of work.
Permafrost specific design guidance limited to civil/foundations, not fully integrated for REI components.	**Add permafrost REI annex:** foundation types for OCS/TPSS in thawing ground, monitoring requirements (ground temp), contingency design for differential settlement; cite CSA PLUS 4011 and extend to electrification assets.
Wildfire risk not fully embedded in electrification standards (longer seasons; equipment exposure; smoke/heat impacts).	**Introduce wildfire resilience requirements:** clearances/defensible space, fire resistant materials/enclosures, smoke filtration for TPSS, emergency operations protocols, heat resistant cabling/insulators; region based trigger thresholds using FSL maps.
Extreme precipitation/drainage criteria lag future IDF reality in rail corridors and substations.	**Update drainage/flood design clauses:** require climate adjusted IDF (CSA PLUS 4013) for conveyance/storage (e.g., +20–25% design increases or modelled IDF), waterproofing/ingress protection ratings for trackside electrical gear, siting/set back rules from floodplains.
Wind/ice load values not climate adjusted in many applied specs (continued reliance on AREMA historic values).	**Adopt climate adjusted radial ice/wind pressure values** and require verification against projected changes (e.g., CanRCM4 LE wind pressure CFs); Jeong, Cannon, and Zhang (ice load deltas); specify design combinations and inspection regimes for galloping.
Grounding and bonding exposed to changing soil moisture/lightning without climate specific design margins.	**Expand grounding/bonding clauses:** require design for higher lightning flash densities (with safety margins), soil resistivity variability (wet/dry cycles), corrosion resistant materials, and surge protection coordination tailored to projected lightning trends.
Accessibility of climate figures not addressed in standards context (narrative exists, but alt text/contrast not mandated). *(Optional, if the standard will include guidance documents)*	**Add an informative annex on documentation accessibility** for climate maps/ figures in standards: require alt text, colour blind safe palettes, and tabular equivalents for critical design values to ensure equitable use by practitioners.

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In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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