Climate Change Vulnerability Assessment of Ontario's Electrical Transmission Sector

Public Technical Report

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EXECUTIVE SUMMARY

Introduction

It is generally accepted that modern economies are fundamentally dependent on reliable and secure electricity systems. Electricity supply interruptions can impact the delivery of other critical infrastructure and services, supporting public health and safety, and disrupt economic activity. Understanding the critical importance of reliable electrical supply, and the need to prevent unsustainable investment in related assets and systems, Ontario's Expert Panel on Climate Change Adaptation recommended a climate change risk assessment of the Province-wide electricity grid (Pearson and Burton, 2009). In March of 2012, the Environmental Commissioner of Ontario reiterated this recommendation (ECO, 2012).

This paper contributes to a better understanding of the implications of climate change for the electrical system in Ontario, with a focus on the high-voltage transmission system, by reporting on a study that included:

- a screening-level climate change and engineering vulnerability assessment of a major electrical transmission station in southern Ontario, including high voltage electrical transmission components within the station and major high-voltage circuits into and out of the station; and,

- a first order evaluation of the types of adaptation measures that could be used to help manage severe weather and climate change-related risks across a broader set of transmission system segments.

Conducted over the 2013-2015 time period, the study was overseen by the Power System Planning staff of the Ontario Power Authority, since amalgamated with Ontario's Independent Electricity System Operator (IESO), and made use of the PIEVC Protocol, an Engineers Canada-developed engineering vulnerability assessment tool (http://www.pievc.ca/e/index_.cfm), and related modules.[1]

[1] PIEVC refers to the "Public Infrastructure Engineering Vulnerability Committee" Protocol that has been developed to assess extreme weather risks to a variety of classes of public infrastructure systems.

Overview of study and assessment

The five main components of the study were:

Case study selection
- Development of criteria for identifying the priority segments of Ontario's transmission system for a climate risk and vulnerability assessment.
- Application of criteria through weighted decision analysis to select case study .

Case study definition
- Refining the system elements to be included, the range of climate-related hazards for consideration.
- Confirming the spatial and temporal scales proposed for the assessment.

Climate information
- Consolidating and, as necessary and possible, deriving new climate, climate change, and impacts information tailored to the requirements of the assessment.
- Developing relevant electricity infrastructure response threshold values.

Assessment and adaptaion options
- Characterization and ranking of climate change risks to the case study transmission systems.
- Multi-criteria analysis of adaptation options through PIEVC Triple Bottom Line Module to determine suitability of potential risk management measures to other comparable segments of the Ontario grid.

Case study selection involved using a criteria framework that supported team members, a Project Advisory Committee (PAC), and IESO staff in prioritizing among potential alternative segments of Ontario's electrical system for assessment. The same parties honed the scope of the assessment, ultimately including the following main infrastructure components and climate parameters:

Infrastructure components: (above ground circuits) 500kV and 230kV transmission towers, conductors, insulators, tower arms; (station, above ground) autotransformers, step-down transformers, breakers; (station, below ground) vaults, transformers, switches, drainage elements, sump pumps; and key third party infrastructure.

Climate parameters: ice storms of varying magnitudes/thresholds (25mm, 29mm, 50mm); EF2+ tornados; other high intensity winds of various magnitudes/thresholds and types; extreme temperatures of various thresholds; and short-duration rainfall (>100mm).

Expert deliberation informed by targeted forensic investigation (of past relevant electrical system failures) and reviews of relevant engineering climatology- and climate design-related literature allowed for the pairing of infrastructure components with relevant climate parameters and performance thresholds. The vulnerability assessment then established current as well as projected likelihoods of the occurrence of each climate parameter/threshold value – historical frequencies of occurrence and projected change by the 2050s – and estimates of expected infrastructure response(s). Ultimately, using the PIEVC process, the likelihood and performance response estimates were converted into point scores according to ordinal scales for "probability" and "severity," respectively. Vulnerability scores were produced by the standard engineering and PIEVC approach of multiplying the probability and severity scores.

In total 667 infrastructure component-climate parameter interactions were assessed.

Inspired by key resiliency-conferring characteristics of the assessed segment of the Ontario grid, the study team adapted and incorporated elements of the PIEVC Triple Bottom Line module within a weighted decision analysis framework for use in evaluating and prioritizing among adaptation options for other parts of Ontario's high voltage electrical system that are characteristically different (e.g., with less built-in redundancy).

General results of the assessment

The assessed segment of the Ontario electrical system has considerable built-in redundancy, including twinned circuits, and alternative circuits feeding common switching stations. Considering these design elements, and existing maintenance and operational procedures, it was determined that in most cases severe climate events, while capable of causing inconvenience and increased maintenance requirements, are not likely to significantly affect the delivery of service.

While differences in levels of vulnerability were identified between assessed 500 kV and assessed 230 kV circuits – a predictable outcome, given that circuits of different voltages are designed in accordance with different load criteria (i.e. higher design load requirements for 500 kV infrastructure) – there was no discernable difference in assessed vulnerabilities between or among circuits of equal voltage. The fact that *two* 500kV circuits and *ten* 200 kV circuits were assessed may suggest it is possible to generalize findings for each circuit type to similar circuits in other parts of the Toronto region.

Upon completion of the analysis, the assessed infrastructure component-climate parameter interactions were categorized as follows:

- 4 High Risk interactions (all temperature and line sag-related);
- 397 Medium Risk interactions;
- 266 Low Risk interactions; and,
- 85 special cases.

The term "special cases" is used to refer to a small number of relatively rare but potentially high-impact climate events and the infrastructure responses they would likely cause. Two types of climate event were identified as posing the greatest risk in this regard:

- Extreme ice accretion arising from ice storm events; and,
- High wind events arising from convective storms (i.e. severe thunderstorm winds, including tornadoes and microbursts).

Events of these descriptions can result in significant system outages and the need for costly repair or replacement of critical infrastructure components, such as support towers and transformers. Furthermore, there is considerable uncertainty associated with projections of future changes in these particular parameters.

Assessment results by main climate parameter

<u>Ice accretion</u>: Though no ice accretion interactions yielded *high* vulnerability scores overall, the assessment did reveal a pattern of potential system-wide vulnerability to ice accretion events, particularly on the 230 kV portions of the system. The current design threshold for the 230 kV system, the lower bound of ice accretion loading considered in this assessment, represents a 1-in-150 year event. Frequencies diminish very rapidly for higher ice accretion thresholds, such that the design threshold for 500 kV circuits, only 5 mm greater than those for 230 kV circuits, represent a 1-in-*500* year event for the same location. Nevertheless, downscaled climate change projections strongly indicate that the frequencies of such events are expected to increase significantly through the period of study relative to historical baseline values. Recent ensemble downscaled climate projections for ice storms in southern Ontario indicated an approximately 40% increase in frequency over 50 years, +/- 6% (Cheng *et. al.*, 2007), while Pearson Airport-specific analyses have suggested even greater potential increases, on the order of 50% (C.S. Cheng, per. comm.).

<u>High winds</u>: High winds were identified as leading to potential system-wide vulnerabilities. Though no *high* vulnerability interactions were identified through the assessments, a number of interactions associated with convective (thunder) storm winds were identified as conferring high-medium levels of vulnerability. The 500 kV system was determined to be somewhat less sensitive to high winds than the 230kV system because of the relatively robust standard of 120 km/hr winds used for its design, as compared to the 110 km/hr standard used for the 230 kV system. Also considered was the potential for debris impacts on transmission system components during high wind events; though the transmission system may be designed to withstand high winds, it may be damaged by secondary impacts not contemplated in design standards. With respect to uncertainty, the effects of climate change on the intensity and frequency of wind events generated by severe thunderstorms are highly challenging both to detect (through analyses of observational data) and project (through currently available climate change projection methodologies). Although several recent studies suggest there will likely be an increase in the frequency of the conditions that lead to severe thunderstorms (e.g. Diffenbaugh *et al.*, 2013), how these changes translate into changes in event frequency and/or magnitude remain highly uncertain.

<u>Extreme Heat</u>: High temperatures and heat waves are anticipated to occur with increasing frequency over the time horizon of the assessment. However, experts at the vulnerability assessment workshops indicated that, overall, the transmission system can accommodate the projected occurrences of extreme heat. One exception may be the interaction of high temperatures with transmission systems crossing transportation corridors, where line sag could potentially result in contact with vehicles. Though new to this region, such impacts could conceivably occur in some Ontario locations under certain future temperature scenarios. Close

assessment of this risk was not possible during the current assessment due mainly to a lack of available data on conductor height above transportation corridors.

Potential adaptation options

Given the generally high level of resiliency exhibited by the assessed segment of Ontario's high voltage electrical system, six adaptation alternatives for other portions of Ontario's grid were evaluated and prioritized using a weighted decision analysis (WDA) framework informed by the PIEVC Triple Bottom Line module. The alternatives and corresponding grid segments were as follows:

Alternative	Description
1	Northern community supplied by single circuit 115 kV line; Twinning, Redundant Design
2	Northern community supplied by single circuit 115 kV line; Enhanced Design, Asset Hardening.
3	Northern community supplied by single circuit 115 kV line; Low Voltage Redirection
4	500 kV transmission corridor carrying supply from major nuclear facility; Asset Hardening
5	Northern communities supplied by 115 kV transmission; Twinning, Redundant Design
6	Northern communities supplied by 115 kV transmission; Local Generation

The WDA scores indicate **Alternatives 1, 5 and 6** do not merit immediate attention, due mainly to the relatively high cost of each of these options. Meanwhile, across the entire range of economic weighting scenarios asset hardening alternatives scored relatively high. When economic factors are most heavily weighted, **Alternative 4**, asset hardening in the 500 kV corridor from a major nuclear facility supplying highly populated areas scores highest, with **alternatives 2 and 3** – enhancing design in the Northern communities supplied by single circuit 115 kV transmission – scoring only modestly lower.

Main recommendations

Monitor frequency of ice storm events. Given the system-wide impacts (especially to 230 kV components) associated with these events, and the potential for more frequent occurrences of higher threshold events over time, it is recommended that likelihood estimates for events at critical thresholds be re-evaluated at reasonable intervals. Furthermore, climate projections of future ice storm conditions should be updated regularly based on the most up-to-date climate science and meteorological observations, including any Ontario-specific data collected over time on recurrence intervals and/or the meteorological set-ups (ingredients) of such events. If either or both empirical observations and/or improved climate projections provide stronger indications that event frequencies are or could be increasing more rapidly than current estimates suggest (Cheng et al. 2007), the overall level of vulnerability associated with these events should be increased accordingly and may merit direct engineering intervention.

Monitor frequency and impact of high wind events. Given the potential system-wide impacts (especially to 230 kV components) of high wind events caused by convective storms, climate projections for conditions associated with high wind events should be updated regularly based on the most up-to-date climate science and meteorological observation. As with extreme ice storms, continued monitoring and recording of these events is critical to understanding future trends and, in turn, future changes in *vulnerability* which may arise. This will require specialized data collection methods and associated training for proper monitoring, beyond passive instrumented climate monitoring. Such techniques may include methods like post-event forensic (impact/failure) investigation, and targeted historical research to identify and classify important past events to improve the historical record of thunderstorm winds impacting electrical transmission systems. If through these continued observations the frequency of impactful events is observed to be increasing, the overall level of assessed system vulnerability should be increased and may merit direct engineering intervention.

Survey transmission system-transportation system crossings. Given the potentially high risk scenarios associated with high temperatures and line sag over transportation corridors, and the lack of data associated with specific line elevations over most crossing locations, it is recommended that the infrastructure owner: survey locations where transmission systems cross transportation corridors; assess line elevations above the corridor; and, determine if line sag under the temperature scenarios projected over the time horizon of the assessment could in fact result in contact with vehicles using the corridors.

Additional forensic analysis of four-wire bundles. Given the limitations posed to the assessment by a lack of information on the performance of four-wire conductor bundles, it is recommended that further forensic analyses be carried out with respect to the performance of four-wire bundles under ice accretion and high wind loading events. Such analyses would improve the overall veracity of future climate change vulnerability assessments of Ontario's electrical system.

Further recommendations

Further recommendations of the study include:

Increase availability of long-term historical climate data within the immediate vicinity of the case study by expanding monitoring to include climatic conditions directly relevant to electrical transmission infrastructure, including measures of extreme wind gusts and ice accretion and associated conditions.

Better integrate forensic information into future assessments, identifying "breaking thresholds" (actual climate thresholds developed through analysis of in-field infrastructure performance), and furthering the development of more formalized climate forensic investigation and analysis. practice in Canada.

Consider development of warning systems based on improved monitoring of weather conditions known to result in the occurrence of such extreme events as EF2+ tornados, ice storms capable of producing 60 mm or greater ice accretion, and extreme heat events.

Conduct a more in-depth TBL analysis of adaptation options to determine the likely costs and benefits of asset hardening in both the Toronto region and in more rural and remote locations.

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1. INTRODUCTION

1.1 Purpose and Structure of the Report

This paper reports on a screening-level climate change engineering vulnerability assessment of a major electrical transmission station in southern Ontario. Conducted over the 2013-2015 time period, the assessment was undertaken with the participation of Power System Planning staff of the Ontario Power Authority ("OPA," since amalgamated with Ontario's Independent Electricity System Operator, or "IESO") and included within its scope the major high voltage electrical transmission system elements within the station and major high voltage circuits into and out of the station.

As the first formal engineering vulnerability assessment of its kind with a focus on climate change and Ontario's electrical transmission system, the intent of the study was to provide a preliminary, screening-level assessment of potentially important vulnerabilities and, equally, insights into which portions of the grid may be sufficiently resilient considering current and projected climate-related impacts.

The structure of this paper is as follows: Remaining portions of **Section 1** describe the background of the study, its origins, goals and logistical background. **Section 2** provides a high level description of the methodology, focusing on the tools used for guidance and analyses (PIEVC Protocol and weighted decision analysis, or "WDA"). **Sections 3** to **7** describe specific phases of the project and associated results. **Section 8** provides conclusions and recommendations, and **Section 9** provides further qualification of these through a description of limitations associated with the assessment. Further technical details are available in **Appendices A through E**.

1.2 Scope and Objectives of the Assessment

The goal of the project was to conduct a screening level, case study-specific climate change vulnerability assessment to inform both immediate risk reduction measures as well as next steps towards a more comprehensive assessment of Ontario's electrical system. By focusing on a case study comprising a well-defined segment of the transmission system with certain key characteristics common to other portions of the grid, the study set out to:

- Assess climate change-related risks associated with the case study, including any lessons that can be drawn for other similar segments or portions of the system;

- Identify and evaluate potential climate change risk management options, based on key characteristics of the particular case study and those of other, comparable, segments of the system; and,

- Identify and discuss potential next steps for advancing the practice of climate change risk assessments and future studies.

1.3 Transmission Infrastructure and Climate Change

It is generally accepted that modern economies are fundamentally dependent on reliable and secure electricity systems. Electricity supply interruptions can impact the delivery of other critical infrastructure and services, supporting public health and safety, and disrupt economic activity. This dependency makes a strong case for improving our understanding of potential vulnerabilities of the electrical system to severe weather events and the influence of climate change. Of more than two hundred Ontario municipalities surveyed, the large majority identified weather and climate-related impacts, along with power outages, as the top-ranked risks in their municipal Hazards Identification and Risk Assessments (HIRA) (MacIver et al., 2009).

According to Jim Burbee, CEO of the Canadian Electricity Association, across Canada electrical systems will require an estimated $347.5 billion of investment between by 2030 just to keep pace with customer demand, as well as investment to replace aging infrastructure. The incorporation of additional infrastructure resilience to deal with the changing climate is likely to represent a small investment incremental to what will need to be spent to refurbish and replace aging infrastructure. Relying solely on retrofits that in the future to adapt to changing climate regimes could result in much higher overall costs. As studies of disaster mitigation have shown (MMC, 2005), a more proactive approach can provide stronger returns on investment.

Recent climate change vulnerability assessments of Canadian buildings, transportation, water, and waste water systems have routinely identified vulnerability to electricity supply interruptions as a key risk factor.[2] Understanding the critical importance of the electrical system, and the need to prevent unsustainable investment in related assets, Ontario's 2007 Expert Panel on Climate Change Adaptation recommended a climate change risk assessment of the Province-wide electricity grid (Pearson and Burton, 2009). In the March of 2012, the Environmental Commissioner of Ontario reiterated this recommendation (ECO, 2012).

Each component of an electrical network can be uniquely sensitive to climate and weather conditions and will often respond differently to a variety of extreme weather thresholds. Ontario's complex and spatially expansive electrical grid consists of many individual segments, nodes and components, including: a highly heterogeneous network of electrical conductors, towers and supports; substations; communications systems (e.g. fault sensing protective relays); and, important inter-connection points to transform high-voltage electricity to lower voltages supplying distribution systems, as well as critical interties between jurisdictions.

1.4 Project Team and Project Advisory Committee

The project delivery team included staff of the IESO, the Ontario Climate Consortium (a university-based climate impacts and adaptation knowledge generation and outreach organization with Secretariat at the Toronto and Region Conservation Authority), and a team of expert consultants (Nodelcorp and Risk Sciences International). Guidance for the project was

[2] Over the past six years, the PIEVC Climate Change Vulnerability Assessment Protocol has been used to conduct nearly thirty case studies across Canada, with respect to transportation, water, and water resources infrastructure, as well as buildings.

provided by a Project Advisory Committee ("PAC"), consisting of key sector representatives and individuals with backgrounds specifically in infrastructure and climate change risk assessment. Table 1 provides the names and affiliations of all Project Team members. Table 2 does the same for all PAC members. The PAC's role also included advising a second assessment, focused on electricity distribution infrastructure in the GTA, and coordinating between the current project and the distribution study.

Table 1. Project Team.

Organization	Name	Role
Independent Electricity System Operator (formerly Ontario Power Authority)	Steven Norrie	Transmission planning – Project Direction
Nodelcorp Consulting Inc,	Joel Nodelman, Joan Nodelman	Engineering risk assessment, PIEVC Protocol, and PIEVC workshop
Risk Science International	Heather Auld Erik Sparling Simon Eng Neil Comer	Climate information/analysis, climate analytics, reporting, and stakeholder engagement
Toronto and Region Conservation/ Ontario Climate Consortium	Chandra Sharma Ian McVey Stewart Duffield	Administrative lead, project oversight, budget Management, climate adaptation research, workshop coordination and reporting

Table 2. Project Advisory Committee.

Organization	Name
Engineers Canada	David Lapp
Brookfield Renewable	Peter Bettle
Consulting Engineers of Ontario	Barry Steinberg
Hydro One Networks Inc.	Bob Singh
Independent Electrical System Operator (Ontario)	David Robitaille
Toronto Region Conservation Authority	Don Haley
University of Western Ontario	Prof. Gordon McBean
Ontario Ministry of Energy	Cheryl O'Donnell
Ontario Power Generation	Tom Lumley
York University	Prof. Mark Winfield

2. METHODOLOGY

2.1 Project Design

The project drew on well-tested climate change vulnerability and risk assessment tools, and strong climatological and engineering meteorology expertise. Recognizing the importance of sustained engagement with the electrical sector, a Project Advisory Committee (PAC) was formed and consulted at regular intervals throughout the project.

The Project included the following main steps:

1) **Case study selection**: With electricity sector representatives, develop and apply criteria for prioritizing the most useful segments of Ontario's transmission system for assessment with respect to severe weather and climate change-related risks and opportunities (see **Section 3**);

2) **Case study scoping**: Support transmission sector representatives in further scoping the severe weather and climate change risk and opportunities assessment (see **Section 4**);

3) **Relevant climate information**: Consolidate and, as necessary and possible, develop climate, climate change, and impacts information tailored to the requirements of the risk and opportunities assessment (see **Section 5** and **Appendices C to E**);

4) **Risk assessment**: Facilitate sector representatives and other technical experts in carrying out the risk and opportunities assessment, in accordance with the PIEVC Protocol, Version 10, including use of the PIEVC Triple Bottom Line Module for the identification and evaluation of potential adaption options (see **Sections 6** and **7**);

5) **Communication of outcomes**: Communicate the process, lessons learned, results, and recommendations through a variety of means, including: a final report, a webinar, and conference presentations (see **Section 8**).

As noted, a related climate change risk assessment, focused on the Toronto Hydro electrical *distribution* grid, was conducted in parallel with this study. Portions of the current report may make reference to findings of the Toronto Hydro Study and *vice versa*. Coordination between the studies, including through use of the (shared) PAC, helped highlight important considerations with respect to interconnections between the systems of study as well as key similarities and differences among their vulnerability characteristics.

2.2 Defining "Risk" versus "Vulnerability"

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability to climate change as[3]:

[3] Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez and F. Yamin, 2007: ***Assessing key vulnerabilities and the risk from climate change. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the***

… the degree to which systems are susceptible to, and unable to cope with, adverse impacts.

They also state:

The concept of risk, which combines the magnitude of the impact with the probability of its occurrence, captures uncertainty in the underlying processes of climate change, exposure, impacts and adaptation.

The PIEVC Protocol considers engineering vulnerability to be a function of the physical properties of a system, particularly its sensitivity to climate related impacts, and the likelihood that the system will be exposed to a defined climate parameter, triggering those sensitivities. PIEVC assessments employ the concept of risk in measuring the *extent* to which a system is vulnerable and how its vulnerability may change in response to changing climate events. The assessments seek to provide a measure of vulnerability, based on relevant climate parameters and system responses.

2.3 The PIEVC Protocol

The ***PIEVC Engineering Protocol***[4] (Protocol) guided the approach in conducting this assessment. The Protocol outlines a five-step process for assessing risk as a measure of vulnerability of infrastructure systems with respect to climate change, as presented in Figure 1.

Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 779-810.

[4] Engineers Canada, ***PIEVC Engineering Protocol for Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate***, Version 10, October 2011

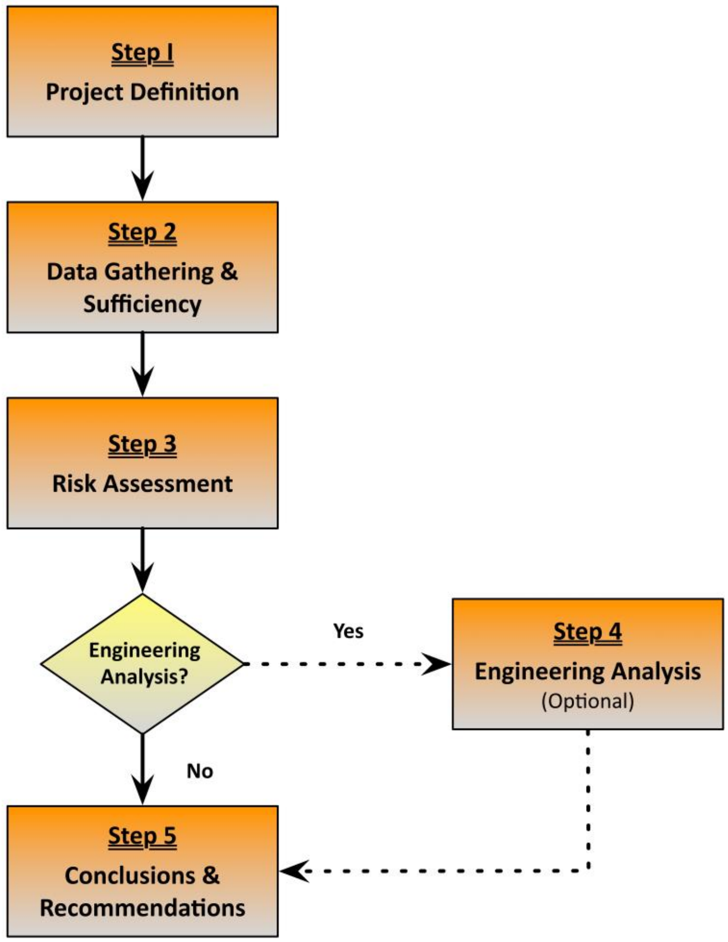

Figure 1. Overview of the PIEVC Protocol.

For the purposes of this study, Step 4, Engineering Analysis was deemed to be outside of the scope of work. Rather, the assessment was conducted as a screening-level study, to identify potential climate related vulnerabilities.

Details of the PIEVC Protocol are outlined in **Appendix A**.

2.4 Weighted Decision Analysis

Weighted Decision Analysis (WDA) is a method used to gain a more objective understanding of comparable alternatives, providing greater insight into the strengths and weaknesses of various alternatives based on a set of common criteria. WDA was used twice during the project, first for case study selection, and again in the final phase under the Triple Bottom Line assessment to compare potential adaptation options.

Details of the WDA Methodology are outlined in **Appendix B**.

2.5 WDA in Case Study Selection

Given the expansive nature of the electricity system, the project team proposed to focus its work on one or, at most, two representative case studies. A first key step of the project was therefore the selection and application of a method for prioritizing among various potential case study options. Case study options represented a selected portion of the electricity system to which the PIEVC Protocol could be applied. WDA was identified as a reasonable method to use, since WDA is meant to help establish an objective understanding of the overall relative suitability of different but comparable alternatives within a given decision context.

The application of WDA for case study selection is outlined in detail in **Section 3**.

2.6 WDA in Triple Bottom Line Assessment

The PIEVC Protocol outlines a Triple Bottom Line (TBL) assessment process based on multifactor analysis and consultation with an appropriate range of stakeholders. In the current study, we used a modified WDA process to achieve the same results.

Normally, TBL is conducted on a range of concrete alternatives to address issues on a specific infrastructure system. When these alternatives have been developed, they would normally incorporate a number of quantifiable factors covering:

- The cost of implementing each alternative;
- Concrete data on how this would mitigate the risk that has been identified; and
- Additional information on the broader social impacts of each alternative.

In this study, we found that the infrastructure was generally resilient to changing climate conditions, as we outline in more detail in **Section 6**. As a result, direct application of the Engineers Canada TBL module to this segment of the Ontario Transmission System did not make intuitive sense (i.e., given the generally resilient nature of the infrastructure under study, there were no significant vulnerabilities that could be addressed by a readily definable adaption alternative). As such, in place of the “typical” TBL analysis the team elected to consider the implications of applying the same elements of system design responsible for conferring high levels of resiliency to the Cherrywood TS and associated circuits to other representative segments of Ontario’s transmission system.

We outline the modifications in detail, and outline the results from the TBL analysis in **Section 7**.

3. CASE STUDY SELECTION

3.1 Main Elements of the WDA Framework

Selection among case study options was based on development and application of a tailored WDA process.

Based on a review of electrical sector extreme weather and climate change risk assessments in other jurisdictions, electrical sector vulnerability and risk assessments more generally, targeted discussions with PAC members, and, discussions with other experts, a core set of criteria was established and developed into a WDA Framework. As per **Appendix B**, these criteria were grouped within two categories: “musts” and “wants.”

3.1.1 Pass/Fail Criteria – “Musts”

Drawing upon discussions with the PAC and the experience of members of the project team, two issues were identified which could conceivably result in the exclusion of proposed case studies from further consideration, namely: a) insufficient data; and, b) sensitivities concerning the public release of critical infrastructure information (“political do-ability”).

Clearly, no matter how carefully selected the site, region, or set of assets, no case study will ever present with “perfect data.” However, in some instances, the data may be so sparse, or of such short duration or poor quality that any related analyses would produce results that would be prohibitively difficult to use and draw lessons from. The intent of the “data availability” criterion is to ensure any such cases are weeded out early. Data availability is further broken down into the following categories, each of which must receive a passing mark:

- Climate data (e.g., temperature, precipitation, and wind data that can be used to derive climate statistics);
- Other environmental data (e.g., data on soil and drainage conditions);
- Infrastructure design (e.g., data on design assumptions for climate-sensitive components);
- Infrastructure operation (e.g., data on peak loading periods);
- Infrastructure maintenance (e.g., data on dates of construction, replacement of major components); and,
- Infrastructure performance (e.g. information on events which impacted infrastructure performance, requiring repair, replacement, upgrade, etc.).

The second of the pass/fail criteria, “political do-ability,” recognizes that past events or other factors may make certain sections of the transmission grid less conducive than others to collaborative study and assessment, and that in some cases a proposed case study may need to be excluded from further consideration because of security concerns related to the public disclosure of critical infrastructure information.

3.1.2 Point-Rated Criteria – "Wants"

The balance of the WDA framework situates point-rated criteria and accompanying indicators within five higher levels of organization called "assessment factors." The relationships between and among assessment factors, criteria, and indicators, and their links to scoring are displayed in Table 3.

Table 3. Relating Assessment Factors, Criteria, Indicators, and Scoring.

Assessment Factor	Criterion	Indicator	Link to scoring
1. Consequence of power disruption for served population	Level of redundancy in system	Proportion of failures which could *not* be addressed through an alternative	Lower redundancy; greater consequence; higher score
	Size of affected population	Number of individuals	Larger population; greater consequence; higher score
	Time to address disruption – remoteness	Average number of hours to access from nearest service centre	Longer response time; greater consequence; higher score
	Time to address disruption – complexity of repair	Typical source of replacement parts	More complexity; longer response time; greater consequence; higher score
2. Utility of case study for transmission sector decision making in Ontario	Representativeness of infrastructure components	% of services (lines) in Ontario which use same components	More representative; greater transferability of lessons; higher utility; higher score
	Representativeness of infrastructure designs	% of services (lines) in Ontario with similar designs	More representative; greater transferability of lessons; higher utility; higher score
	Representativeness of climate related sensitivities	% of climate conditions or event types of interest to case study which are also experienced in other regions of Ontario	More representative; greater transferability of lessons; higher utility; higher score
3. Potential vulnerability of the identified system	Susceptibility to harm related to technical, workforce, or organizational factors (i.e. non-climate factors)	(No specific indicators were applied)	Higher vulnerability; greater priority; higher score

Assessment Factor	Criterion	Indicator	Link to scoring
	Coping capacity related to technical, workforce, or organizational factors	(No specific indicators were applied)	Higher vulnerability; greater priority; higher score
4. Consequence of power disruption for service provider	Reputational	(No specific indicators were applied)	Higher potential for reputational impact; higher score
	Financial	(No specific indicators were applied)	Higher potential for financial impact; higher score
5. Consequence of power disruption for oversight authority	Reputational	(No specific indicators were applied)	Higher potential for reputational impact; higher score

3.2 Outcomes

A list of possible case studies was formulated based on advice from the IESO's Power System Planning, Transmission Integration group which was then evaluated using the WDA framework. These included:

- The Cherrywood TS to Claireville TS 500kV corridor (transmission corridor connecting two major transmission stations in the Greater Toronto Area (GTA));
- Development of a second North-South transmission connection;
- 500 kV / 230 kV transmission from Bruce Generating Station to the GTA;
- Transmission corridors in southern Ontario potentially at risk due to tornadoes and ice storms; and,
- Proposed transmission system expansion(s) in the far North.

The list of potential case studies reflected the diversity of Ontario's high voltage electricity grid, which covers a large geographic area and includes many different component types of varying ages, sizes, voltages and design characteristics across the province.

Ultimately, case study selection was based on: application of the WDA framework; PAC deliberations; an effort to align this assessment with the Toronto Hydro distribution project; and guidance and recommendations from the IESO.

The Cherrywood to Claireville 500kV corridor, with a specific focus on a major Transmission Station in the GTA was selected for assessment.[5]

[5] For the purpose of this public report, the name and location of the specific transmission station case study is not disclosed due to security concerns related to the disclosure of critical infrastructure information.

4. CASE STUDY SCOPING

The Case Study Transmission Station and connected circuits, including the 500 kV corridor and 230 kV circuits, comprise a number of infrastructure components that were itemized and characterized in order to scope the extent of the vulnerability assessment. Infrastructure components which comprise the case study have been classified into five main categories: above ground circuit, above ground on-site, below ground, “miscellaneous,” and third party infrastructure. The above ground circuit category includes all major components which comprise electrical circuits connected to the transmission station, and include conductors and support structures. Several kinds of support structures were identified, including the familiar steel lattice supported self-supporting[6] towers carrying one, two or more circuits, monopole support towers, and in one case wood pole supports. These structures are designed for climatic loading under CAN/CSA No. 22.3 60826 (CSA 2010), with different climatic load design values specified for 230kV and 500 kV circuits. Support structures are further separated into arms, insulators and skywires, structural components which were explicitly identified by workshop participants as possible points of failure under climatic loading, specifically for ice accretion events.

Above ground on-site components consist of high-voltage switches, breakers and transformer gear which comprise the main components responsible for the functioning of the transmission station. In contrast to other transmission stations in which switchgear is sheltered or semi-sheltered in buildings, the case study station is a physically large station with exposed components. The exposed nature of above ground infrastructure at the station was of particular interest for consideration of climate impacts. Below ground infrastructure has been characterized more generically, mainly due to a lack of information regarding certain site-specific characteristics.[7] However, these components were included in the assessment due to known sensitivities exhibited by other stations in Ontario (particularly for extreme rainfall events), as well as to highlight the importance of having more complete infrastructure component characteristics. The “miscellaneous” category was developed to capture personnel and site maintenance characteristics.

Finally, the third party infrastructure category was defined to capture interactions between the electrical transmission infrastructure and adjacent systems and buildings. The transmission station and associated transmission corridors are located near and within urban, sub-urban, industrial and commercial environments, and also cross multiple transportation and utility corridors. These important elements include adjacent buildings of different classes (housing, industrial, and commercial[8]), other electrical infrastructure (electrical distribution, power

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[6] These were “self-supported” towers as opposed to V-guyed towers, which consist of V-shaped steel lattice structures that are supported by steel guy-wires.

[7] Obtaining access to operating transmission stations can be challenging due to the presence of energized equipment and safety protocols.

[8] These are particularly found along connecting transmission corridors.

generation), transportation corridors (400 series highway, roads, streets, rail lines), and finally naturally vegetated areas (forests). Hence, it was clearly identified in the initial infrastructure characterization process that emphasis on potential interactions with third party infrastructure was of particular importance from a climate change perspective.

5. CLIMATE ANALYSIS

The risk assessment methodology makes use of what are best described as climate and weather "parameters," magnitude and/or frequency measures of climate elements[9] which define conditions which could result in damage to or disruptions in service from a defined infrastructure system. Put differently, these parameters define particular atmospheric conditions to which the infrastructure is known to be "sensitive." A climate or weather "event" can be defined as an acute occurrence such as a thunderstorm, drought, flash flood, tornado, or heat wave that results from the combination of a particular set of climate conditions. Under this assessment, the term "climate parameter" is used to describe either discrete weather events or measurements of climate conditions, both of which are parameters within the greater context of the engineering risk assessment.

Of particular importance to the PIEVC assessment are so-called "complex" events. These consist of either two or more climate events occurring concurrently and/or in succession, or one or more events acting in concert with human induced conditions (e.g. debris blocking storm water drainage). These "complex" events will generally result in far greater impacts to the built environment than individual events acting alone. The climate analysis also identifies "small scale" or "localized" events of importance to the study. These are weather events that generally require a very specific set of atmospheric conditions to occur, and which tend to produce impacts over much smaller temporal and spatial scales (i.e., can be short-lived but intense and very localized). These tend to elude most established meteorological observation networks and are not often well captured by existing climate observations, but also tend to produce *very* significant impacts when they interact with the built environment.

When these important climate and weather parameters are defined, the probability scoring process can begin.

5.1 Climate & Weather Parameter Identification and Selection

The selection of relevant climate parameters and associated impact thresholds was informed by:

- **Literature Review** of design loads in codes and standards as well as related published literature;
- **Practitioner consultation**, including targeted interviews, email communications, and workshops; and,
- **Forensic analyses** of system specific case studies and/or relevant cases in the published and "grey" literature.[10]

[9] i.e. The basic elements which describe the state of the atmosphere at any given time, meaning temperature, precipitation, wind, pressure and humidity.

[10] Grey literature is academic literature that has not been formally published.

These three methods are typically employed together in an iterative fashion in order to properly identify the relevant climate parameters in adaptation studies.

5.1.1 Literature Review

The literature reviewed for this study included *Design Criteria of Overhead Transmission Lines* (CSA 2010) as well as numerous journal articles describing climate sensitivities of electrical transmission systems within Canada and other mid-latitude jurisdictions (see **Appendix C** for the literature review).

Design values in codes and standards generally offer an excellent “first guess” to determine impact thresholds, providing information on not only baseline climatic design values, but on safety factors, load combinations, and so on. These values can also be used as a basis for discussion with practitioners, to determine if there are local modifications for in-field infrastructure.

The literature review (see **Appendix C**) had initially identified a significant number of both individual and combination events which could be important for transmission line risk assessment; however, through practitioner consultation, the assessment team was able to significantly reduce the number of climate elements to a workable number of key areas of concern.

5.1.2 Practitioner Consultation

Discussion and consultation with practitioners is invaluable for studies of this nature. Practitioners can describe important historical events and their impacts, relevant logistical and operational elements of the system, and new and emerging problems that may not be documented elsewhere. More generally, practitioners can provide guidance on where problematic interactions tend to arise and what can be done to reduce those impacts (i.e. adaptation measures).

A number of practitioners from the IESO and Hydro One were first contacted via email and interviewed on an individual basis beginning in March of 2014. Following these interviews, two technical workshops were held, both hosted at the IESO’s headquarters, on August 20th and October 20th 2014. Assumptions regarding climate elements and the proposed infrastructure itemization were presented, discussed and modified. Both workshops were pivotal in correcting initial assumptions either based on material from the literature reviews or made by project team members when filling out worksheets. For example, extreme high temperatures were initially thought to generate significant impacts to the transmission system, while practitioners strongly indicated in subsequent discussions that this was not the case. Participants stressed that, even with projected changes in extreme temperatures, transmission equipment should be resilient enough to continue operating without major difficulties.

Practitioner consultation also revealed that the industry stakeholders participating in the transmission case study were strongly interested in “low-probability/high impact events,” reflective of the deterministic contingency assessment methodologies which for decades have been required by the Reliability Standards established for interconnected power systems in North America and specific to Ontario (e.g., NERC, NPCC and the IESO's ORTAC criteria). These standards account for low-probability/high-impact events involving the loss of more than two power system elements by employing a risk-based approach is employed considering the probability and the consequences of events of this nature. The number of these types of extreme events that can be studied in detail is limited, but climate change may be leading to more types of these types of scenarios being credible contingencies in terms of the probability of their occurrence and the severity of the consequences to the electrical system when they happen.

5.1.3 Forensic Analyses

Forensic analysis is the evaluation of past events through the application of scientific techniques and understanding to establish facts. It is meant to diagnose the causes and factors contributing to a given infrastructure failure incident. In the context of extreme weather and climate events, we can evaluate the meteorological conditions associated with an incident and compare those to impacts produced (i.e. what was damaged, how was it damaged, etc.) as well as the supposed design capacity of the impacted system (i.e. what was it designed for).

Because of the study team's particular interest in better understanding the likelihood of climate extremes capable of triggering catastrophic failures in the electrical system, it was necessary to identify examples of historical climate-related events of a catastrophic nature, both in Ontario and in other jurisdictions with similar climatic conditions, then "work backwards" to determine the characteristics of the severe weather event (level of intensity, duration) that produced the failure. The purpose of conducting a brief but informative "cross-incident" analysis is to determine important event types and thresholds. A number of important historical events were identified through these searches (see **Appendix D** for a list of important historical events). Some search criteria were based on practitioner consultation,[11] again showing the importance of combining approaches outlined above.

5.2 Climate Parameter Analyses

The following sections describe the information sources and methods used for calculating current and future probabilities for important climate parameters.

[11] For example, several practitioners at OPA/IESO had asked if there were any cases of direct tornado strikes on transmission stations, to help understand possible impacts if one were to occur in Ontario. While there are no known cases in Canada, there are several reported in the United States. This led to an understanding of required tornado severity for significant impacts, and also to the understanding of the importance of secondary debris impacts.

5.2.1 Historical Climate

Future conditions cannot be well understood until current and historical climate conditions are quantified, particularly with regards to already existing vulnerabilities and thresholds present within the transmission system.

Within Canada, Environment Canada's climate station network generally remains the source of the most reliable and highest quality long term climate record. While there are numerous climate stations in the Greater Toronto Area, detailed *hourly* weather data are usually only available from airport locations, and hence the majority of historical climate information used in this analysis is based on records from Pearson International Airport, with further contributions from Buttonville and Oshawa Municipal airports where appropriate.

Stations can vary significantly in the length of historical observation periods, which can present a problem for historical analysis when observation periods may be too short in duration to provide "meaningful" statistical analyses, hence the primary reliance on the Pearson Airport climate record. In general, longer observation periods are better to understand the historical frequency of events. A period of 30 years, referred to as a climate "normal" period, is generally accepted internationally as a reasonable record length for confident assessment of climate parameters and detection of important trends.

However, in the case of small scale events, the authors have had to modify their methods (e.g. using averaging periods greater than 30 years) or have consulted alternative data sets (e.g. the historical tornado database). Many of the small scale events described below which required specialized treatment for climate *projections*, were also subject to alternative *historical* methods of analysis.

5.2.2 Future Projections

The main sources of future climate projections are so-called Global Climate Models, or "GCMs." The latest International Panel on Climate Change (IPCC) 5th Assessment Report (AR5) provided results from 40 models, produced and operated by modeling centers from around the globe. These models provide many of the basic projections used in evaluating potential future trends in climate parameters.

For each climate parameter, all available models were used in an "ensemble," meaning the results from all models were combined to obtain a mean value. The use of ensembles is considered by the IPCC as a best practice for climate analyses (IPCC, 2012).

GCMs require greenhouse gas "emissions scenarios" as inputs for the calculation of projected future conditions, and the latest IPCC AR5 has introduced a new method of describing future changes in emissions. Representative Concentration Pathways, or RCPs, describe explicitly the expected increase in the global energy balance generated by increases in greenhouse gases. The highest pathway, RCP 8.5, indicates an increase of 8.5 watts of additional energy per square meter under future climate conditions. It is referred to as the "business as usual" emissions scenario, provides the best fit based on historical trends in global emissions, and was the scenario used for this project (as well as the Toronto Hydro electrical distribution PIEVC project).

5.2.2.1 The "Delta" Method

For this assessment, projections were produced using the so-called "Delta-method". GCMs were first evaluated to determine changes from their own respective baselines. The difference between model baseline and projected conditions is then applied to the *observed* baseline calculated from historical climate observations. For example, if the GCM ensemble indicated an average increase or "delta" of 2 degrees between the baseline period and the 2050's, and a given station shows an average annual temperature of 3°C, then the projected annual average temperature for that location for the 2050's becomes 5°C. This is done to reduce the impact of any internal biases which may be inherent within the models. Measures of variability (e.g. range of values) between models within the ensemble further provides an indication of the level of uncertainty associated with these projections.

5.2.2.2 "Small Scale" Events

Many high impact atmospheric events tend to occur on much smaller spatial and temporal scales than are covered by GCMs. Two main strategies have been developed to help address this, and both were employed to determine projections for more localized and shorter duration climate parameters and weather events analyzed.

Regional climate models,[12] or "RCMs," attempt to address the spatial and temporal scale limitations by covering restricted geographical areas and using much smaller vertical and horizontal grid spacing than GCMs. However, these still rely on GCMs to provide boundary conditions for areas outside of their coverage, as well as providing the initial conditions for the RCM. Some of the results used in Phase II were generated using the CANRCM4 model, and a discussion of associated uncertainties can be found under the specific descriptions for those elements. Where possible, these were compared to analogous estimates from GCM projections, since the scale and complexity of RCMs render them more prone to problems such as numerical instability.

Statistical downscaling studies attempt to solve the spatial scale challenges by developing statistical links between GCM scale climate conditions and localized, short duration events. Historical, point location climate data is compared with conditions on the scale of GCM grids. Statistical links, so called "transfer functions", are then developed based on these relationships. After GCM projections are developed for a given future period, these transfer functions are then used to "downscale" GCM projections back down to local scales. Although much less computationally intensive than RCMs, individual studies still require significant expertise and

[12] These are sometimes referred to as "dynamical downscaling" methods, to provide an analogous term to alternative "statistical downscaling" methods.

time for proper execution, and hence the project made use of previously published statistical downscaling studies for projections (Cheng *et al*. 2011, Cheng 2014).

Finally, in one case, climate change projections were also compared to a “climate analogue,” which refers to locations in other geographical areas which possess historical climates that resemble in many respects the future climate of the study area. The future temperature regime for the 2050’s for the GTA is very similar to the current and historical climate of northern Kentucky. While not an exact comparison – there are significant differences in regional geographical characteristics, for example – rough, “order of magnitude” comparisons – which can be made to help further determine if climate change projections are in fact realistic.

5.3 Probability Scoring of Climate Parameters

For the majority of climate parameters, both historical records and quantitative estimates of projected climate conditions were generally available, allowing the team to use **Method** B for the majority of climate parameters assessed in the project. **Method B** describes the scoring method in which PIEVC probability scores (integer values) are linked directly to the percentage probability of occurrence of a given parameter over the course of the study period. This is in contrast to **Method A**, in which, in the absence of numerical values, verbal descriptions of probability are used (e.g. “likely”, “highly unlikely”) to develop probability scores. Probabilities were defined in this study as the likelihood of a defined climate parameter occurring during the study period (i.e. next 35 years) for a single point location. Converting probabilities into either line or area targets was initially considered; however, the sections of the transmission corridors considered in the case study were not of sufficient length for the probability *scores*[13] to be significantly affected. The study computed both historical frequencies and those applying climate change projections to identify any potential changes in the likelihood of each parameter. Annual frequencies were first calculated based on historical data. These were then converted to a probability of occurrence over the 35 year study using extreme value return period estimates assuming a normal statistical distribution. These percentages were then converted into the 0-7 probability scores based on Method B, with the occasional use of Method A when empirical or modeled data were not available. Following this, any available numerical estimates of future projected changes in parameters and event frequencies were applied to historical data, resulting in estimates of the projected, future probabilities. These were again converted into probability scores in the same fashion as historical probabilities.

The climate parameters and associated probability scores are described below in Table 4. Details on specific analyses associated with each climate parameter can be found at the end of this report in **Appendix E**. Please note that all percentages regarding both historical and future projected probabilities are **approximate** and refer to the percentage probability over the full 35

[13] Large changes in absolute probability are needed for single digit changes in probability scores, particularly for scores in the 0 to 5 range (e.g. an approximate doubling in probability from 5% to 10% to increase the score from a “2” to a “3”). Hence, for low-probability events such as tornadoes, line length factors for corridors in question would increase probabilities by only 20-30%, which is insufficient to change the overall probability score.

year period of study. Scores for which data was insufficient or lacking are indicated as “professional judgment,” with details explaining the reasoning associated with score values provided in the footnotes.

Table 4. Summary of Climate Parameters.

Climate Element	Threshold	Source	Probability of Occurrence Historical	Probability Score Historical	Probability of Occurrence Future	Probability Score Future
Ice Storms	**24 mm radial ice accretion (older lines)**	Design Value: CSA Standard CAN CSA 22.3 No.60826-10	20%	4	>30%	5
	29 mm radial ice	Design Value: CSA Standard CAN CSA 22.3 No.60826-10	<7%	2	~10%	3
	50 mm radial ice accretion	Design Value: Practitioner Consultation (Post-Ice Storm ’98) Special Case – low probability but very high severity	Prof. Judgment (est. ~1%)	1	Prof.[14] Judgment (est. ~1%)	1
Tornadoes	**(E)F-2+**	Historical/Forensic Review of Cases Special Case - low probability	~0.3%	1	~0.3%	1

[14] Return periods for 50 mm radial ice accretion events were estimated by the climate team based on historical data for regions adjacent to the study area. While such events have never been documented in Ontario (though this does not mean they have never *occurred*), a small number of events at or near this threshold have been documented in Michigan and northern New York in the past century (Klaassen *et. al*., 2003). When combined with northward shift in ice storm tracks indicated by climate change projections, such events were deemed to be highly unlikely but remain within the realm of possibility.

Climate Element	Threshold	Source	Probability of Occurrence Historical	Probability Score Historical	Probability of Occurrence Future	Probability Score Future
		but very high severity				
Other high-impact wind events (microburst, derecho, etc.)	**120 km/h +**	Historical/For-ensic Review of Cases + CSA Standard CAN CSA 22.3 No.60826-10	Prof. Judgment (est. ~40%)	5	Prof.[15] Judgment (est. ~40%)	5
"Large Scale" wind storms[16]	**110 km/hr**	Design Value: CSA Standard CAN CSA 22.3 No.60826-10 (Reliability Level 2; 230 kV)	20%	4	>30%	5
	120 km/hr	Design Value: CSA Standard CAN CSA 22.3 No.60826-10 (Reliability Level 3l 500 kV)	<7%	2	10%	3
Extreme Temperatures	**35°C Maximum Ambient**	Lit review; IEEE Standards (Transformer operating temperatures)	100%	7	100%	7

[15] Estimate based on occurrence of extreme winds associated with severe thunderstorms. These probability scores were further vetted with workshop participants. While there are indications of potential increases in high-impact wind events due to climate change, quantitative estimates are lacking.

[16] Design winds in codes and standards generally refer to winds produced by "large scale" low pressure systems. These differ from thunderstorm winds in that, while generally less intense, they are widespread and long lasting.

Climate Element	Threshold	Source	Probability of Occurrence Historical	Probability Score Historical	Probability of Occurrence Future	Probability Score Future
	40°C Maximum Ambient	Lit review; IEEE Standards (Transformer operating temperatures)	25%	4	100%	7
	3+ Consecuti-ve Days >30°C (Heat Wave)	Enter rational for Infrastructure Threshold here. Identify reference to code or standard if relevant.	100%	7	100%	7
Extreme Rainfall	**100 mm in short period + antecedent**	Forensic Analysis (July 8, 2013 Event)	>75%	6	>75%[17]	6

[17] Expected *increasing* trend in this parameter with climate warming; however, magnitude of increase unknown.

6. INFRASTRUCTURE VULNERABILITY ASSESSMENT

6.1 Overview of Severity Scoring

As outlined in **Appendix A**, the team used a blend of PIEVC Protocol Severity Scoring Method D and Method E for this assessment. Scores were based on the professional judgment of the project team and verified through stakeholder consultation at workshops. Initial severity scores were established through a series of interactive working sessions that allowed for score review, refinement, and justification by the project team. These initial scores were then ground-truthed with infrastructure experts over the course of two vulnerability assessment workshops, resulting in the assignment of final scores and accompanying rationales.

6.2 Vulnerability Assessment Workshops

The vulnerability assessment workshops were held on August 20, 2014 and October 20, 2014. Subsequent to the workshops and based on input from participants, the project team revised and incorporated new climate parameters and adjusted severity scores, for use in the final analysis.

6.3 Assessment Results

6.3.1 General Observations

The assessed segment of the Ontario electrical system has a great deal of built-in redundancy, including twinned circuits, and alternative circuits feeding common switching stations. Considering these design elements, and existing maintenance and operational procedures, workshop participants indicated that in most cases acute climate events, while cable of causing inconvenience and increased maintenance requirements, are not likely to significantly affect the delivery of services from the assessed station and circuits.

As already noted, for the sake of comparison ***two*** 500 kV and ***ten*** 230 kV transmission circuits were assessed. While differences in levels of vulnerability were identified between the 500 kV and 230 kV circuits – a predictable outcome, given that they are designed in accordance with different load criteria (i.e. higher design load requirements for 500 kV infrastructure) – there was no discernable difference in assessed vulnerabilities between or among circuits of equal voltage. As such, it may be possible to generalize findings for each circuit type to similar circuits in other parts of the Toronto region.

6.3.2 Overall Risk Profile

In this assessment, we considered 13 climate parameters and 81 infrastructure components, yielding a total of 1,053 possible interactions. Following consultation with experts and workshop participants, a subset of 667 climate-infrastructure interactions were deemed relevant and became the focus of the assessment. Upon completion of the analysis, the identified risks could be categorized as follows:

- 4 High Risk Interactions
- 397 Medium Risk Interactions
- 266 Low Risk Interactions
- 87 special cases

For the most part, we observed the assessed portion of the transmission system to be generally resilient to changing climate conditions. However, we also noted a pattern of vulnerabilities associated with relatively rare climate events which can lead to very significant infrastructure responses. Two categories of events are most striking:

- Ice accretion arising from severe ice storm events; and,
- High wind events arising from convective storms (i.e. severe thunderstorm winds, including tornadoes, microbursts, etc.).

While rare, these events can result in significant system outages and the need for costly repair or replacement of critical infrastructure components such as support towers and transformers. Because of their low probability of occurrence, these events do not necessarily receive high overall risk scores under the current PIEVC methodology, and are currently described as "special cases". However, if and when they do occur, they can cause severe impacts. Because of this and because of the high levels of uncertainty associated with projections of change in these particular parameters in the future, these two event types in particular are deserving of ongoing monitoring and attention.

In the following sections, we summarize results for each of the relevant climate parameters.

6.3.3 Vulnerabilities by Climate Parameter

6.3.3.1 Ice Accretion

Ice storm events can and do lead to significant service interruptions, with the most notable recent occurrences of widespread impacts to portions of the Ontario Transmission System associated with the January 1998 ice storm (e.g. Klaassen *et. al.*, 2003). The current design threshold for the 230 kV system, the lower bound of ice accretion loading considered in this assessment, represents a 1-in-150 year event. Frequencies diminish very rapidly for higher ice accretion thresholds, such that the design threshold for 500 kV circuits, which is only 5 mm greater than those for 230 kV circuits, represent a 1-in-*500* year event for the same location. However, when severe ice storms *do* occur, they can produce very severe outcomes. Downscaled climate change projections strongly indicate that the frequencies of such events are expected to increase significantly through the period of study relative to historical baseline values. In our assessment, we noted that there is a pattern of medium risk associated with these events over the time horizons of the assessment. This is particularly true of the 230 kV portions system, which is notionally designed to a 24 mm radial ice accretion standard, compared to the 29 mm standard applied to the 500 kV System.

6.3.3.2 230 kV (24 mm)

On the 230 kV system, potential vulnerabilities were identified with respect to ice accretion on towers, insulators and tower arms. Workshop participants noted that tower arms would be generally more vulnerable to ice accretion than the towers themselves. Participants also noted that wooden poles were more vulnerable to these events than steel poles, as their experience has shown that wooden poles are more likely to fail earlier in ice storm events. Also of note were significant changes in probabilities associated with projected increases in event frequency, from ~20% probability of occurrence (every 35 years) under historical conditions increasing to over 30% when downscaled projected changes are incorporated.

6.3.3.3 500kV (29 mm)

On the 500kV system, the risk pattern was much less pronounced, largely due to the higher overall design ice accretion standard for these systems. When incorporating climate change projections for 500 kV design threshold values, estimated probabilities of 29 mm icing events over the 35 year time horizon only increased from ~7% to ~10%.

6.3.3.4 More Robust Design (50 mm)

At the workshops, participants noted that in many cases the transmission system has been designed to a much more robust 50 mm ice accretion standard. In these cases we noted that there was no significant ice accretion risk associated with changing climate conditions over the time horizons of this assessment, mainly due to the extreme rarity of events of this magnitude. Application of projected climate trends to the estimated 1% probability of occurrence does not result in a substantive change to the risk score, even with significant increases in frequency (e.g. doubling or tripling of probability). A 1% probability of occurrence over 35 years represents a return period of greater than *3,400 years*.

6.3.3.5 A Pattern of Risk

While none of the ice accretion interactions yielded a *high* risk score overall, the assessment did reveal a pattern of system-wide vulnerability to ice accretion events, particularly on the 230 kV segments of the system. We have noted, and several workshop participants confirmed, that in some circumstances, it would be reasonable to expect the 500 kV system to remain in service while significant elements of the 230 KV system may be out of service due to ice accretion events. A pattern of vulnerability occurs when a particular climate event causes vulnerability in multiple areas of an infrastructure system. The vulnerability is not restricted to one location or one particular infrastructure component. Rather, vulnerabilities exist, to a greater or lesser extent, across the entire system.

Ensemble downscaled climate projections for southern Ontario ice storm events resulted in uncertainties (model "spreads") on the order of ±6%[18] about an average increase of ~40% for southern Ontario (Cheng *et. al*. 2007), and specific analyses using observations from Pearson International Airport indicate even *greater* increases of approximately 50% for that location (C.S. Cheng, pers. comm.). Applying these ranges to the Pearson Airport specific analyses still result in projected increases from 20% to >30%, or probability scores between 4 and 5, resulting in the same medium risk score indicated by applying the ensemble average. However, as with other downscaled climate projection studies, Cheng *et. al*. (2007) indicated a pattern of greater frequency increases for higher thresholds (coupled with greater uncertainty), suggesting that for the most extreme events, significant increases in frequency beyond those suggested by ensemble averages are indeed possible, but the magnitude of these changes is unknown.

6.3.4 High Winds

High winds can also lead to system-wide vulnerabilities. However, once again we note that no high-risk scenarios were identified through the vulnerability assessment. Rather, we note high-medium risks associated with convective storms. Also we noted that once again, the 500 kV system is somewhat less vulnerable to high winds due to a more robust design standard for winds of 120 km/hr on the 500 kV system, compared to 110 km/hr on the 230 kV system.

Workshop participants also noted a potential pattern of risk associated with debris impacts on transmission system components during high wind events, also consistent with a number of historical incidents identified during the initial phases of the project. The concern in this regard is that, even though the transmission system may be designed to withstand high winds, it may be damaged by secondary impacts that are not contemplated in design standards.

6.3.4.1 230 kV with > 120 km/hr Convective Storm Winds

The most significant overall pattern of risk was noted for severe thunderstorm winds. While we observed no high risks, we did note system-wide high-medium risks associated with convective winds in excess of 120 km/hr. While we may anticipate more of these events in the future, we anticipate that they will remain a relatively rare event at any given location; a probability score of 5, within the context of this assessment, corresponds to an approximate[19] return period of about 1-in-70 years. However, given the overall pattern of risk associated with these events, this is an area where there is merit in establishing ongoing monitoring of convective storm events and associated impacts. If storms of this nature become much more frequent, there may be merit in upgrading 230 kV System components to withstand higher winds, such as those for which the 500 kV system components have been designed. This is not an immediate or urgent recommendation, but rather a situation that requires periodic review and assessment.

[18] Variability in result are given for the 95% confidence interval.

[19] Again, as indicated in Table 4 in **Section 5**, this is a professional estimate based on the experience of both the climate analytical team and electrical transmission practitioners.

6.3.4.2 Significant Tornados (EF-2+)

Tornado events were found to yield no significant pattern of vulnerability. However, tornado events can result in very significant damage to system components. Tornado events can impact linear transmission systems in a variety of ways. Should the tornado cut across the system, it can result in localized damage to system components. Should the tornado track along the transmission system right of way, the impact could be much more significant. Though the latter scenario is again much less likely than the former, several cases of this occurring, both in Canada and the United States, have already been documented.

Tornado events, while very rare, with point probabilities based on historical observations of <1% over a 35 year time horizon, they are nonetheless notable and, while they do not yield high-risk values in vulnerability assessment, they are worthy of attention. These events do not demand an engineering response such as asset hardening, but should instead be identified in terms of emergency response procedures.

6.3.4.3 A Pattern of Risk

While none of the infrastructure-wind interactions yield high-risk scores, the overall pattern of medium risk and system-wide vulnerability to high winds in excess of 120 km/hr is notable, particularly on the 230 kV system.

Severe thunderstorm winds are perhaps the best example of localized, small scale events and, as discussed, the effects of climate change on the intensity and/or frequency of this class of weather event are far more challenging to either detect through analyses of observational data, or project through currently available climate change projection methodologies. Although several recent studies suggest there will likely be an increase in the frequency of conditions leading to severe thunderstorms (e.g. Diffenbaugh *et. al*. 2013), how these changes translate to changes in event frequency and/or magnitude remain unknown.

A second source of uncertainty, and very likely an escalation factor for associated risks, is the consideration that electrical transmission support structures are designed for wind loads produced by "large scale" wind storms (i.e. large scale low-pressure systems). Severe thunderstorm wind events in general, and microbursts and tornadoes in particular, are known to differ significantly in their structural loading characteristics from "regular" winds produced by low pressure systems. This is again an indication that current design standards and methods may not address this class of event and may further contribute to overall risk associated with severe thunderstorm winds.

6.3.5 Extreme Heat

High temperatures and heat waves are anticipated to occur with increasing frequency over the time horizon of the assessment. However, experts at the workshops indicated that the transmission system can accommodate the projected occurrences of extreme heat. The participants indicated that, through past experience and knowledge of the design of the infrastructure elements in question (e.g., conductors, insulators, support towers, etc.), that the system as it is currently designed and engineered would be able to withstand the temperatures as projected by the climate models. System planners today use an ambient temperature of 35 degrees Celsius, with no wind, as a planning assumption for the transmission system. This is only an assumption for planning. Planners understand that the electric power system components are able to withstand temperatures higher than 35 degrees. As a result, overall the system has been assessed as resilient to the temperature profiles anticipated over the time horizon of the assessment, with the exception of high temperatures causing transmission line sag and interacting with transmission systems crossing transportation corridors.

Workshop participants raised concerns over line sag associated with high temperature resulting in transmission lines potentially coming into contact with vehicles. While this has never been encountered in this region[20], participants suggested that, given the future increases in frequency of extreme temperatures anticipated in the assessment, line sag of this magnitude is conceivable and that in some locations this could be a concern.

This concern merits closer scrutiny. Within the scope of this assessment we were unable to explicitly identify locations where this could potentially occur, mainly due to a lack of available data regarding conductor height above transportation corridors. As a result, while this has been scored as a high risk, we do not recommend immediate engineering response. Rather, we recommend that the infrastructure owner survey areas where transmission lines cross transportation corridors to determine if transmission lines have sufficient elevation to prevent contact with vehicles if the lines sag due to extreme heat. With this additional information, the infrastructure owner will be able to determine if this is in fact a high risk. If it is, they will have sufficient data to assess appropriate engineering responses. If it is not, they can lower the risk scores for this issue to more moderate levels.

[20] Contact between sagging lines and vehicles has been documents in other locations (e.g. Australia; McEvoy *et. al*., 2012).

7. TRIPLE BOTTOM LINE ASSESSMENT OF ADAPTATION OPTIONS

7.1 Modifying the PIEVC TBL Methodology

7.1.1 Rationale

The PIEVC Triple Bottom Line (TBL) Module outlines a decision support system designed to aid organizations in determining a course of action for adapting infrastructure assets and services to climate change impacts. It is a recommended but optional follow-up to the Vulnerability Assessment Module of the Protocol.

There are three steps to the Module and each step is supported by an associated worksheet. The worksheets parallel the Protocol steps and are provided to allow the practitioner to clearly document each step of the process. As appropriate, the Protocol allows practitioners to modify the existing worksheets or ***develop their own tracking system for their particular assessment***.

The transmission line vulnerability assessment determined that the power transmission system in the Major Transmission Station case study area (main case study area) is generally resilient to changing climate conditions. As such, the results from the assessment do not lend themselves to the application of the PIEVC Triple Bottom Line Module (TBL). The PIEVC TBL process requires the identification of specific engineering adaptation responses, costs, and associated environmental and social outcomes that would arise from implementing the alterative. The assessed segment of the Ontario transmission system was found to be resilient to such a degree that identification of meaningful engineering responses, such as asset hardening or other structural modifications could not be readily established.

The resiliency in the case study area arises mainly from the redundancy of the networked power system, and capacity to tolerate relatively high design loadings that have been engineered into the electrical transmission system over a long period. However, such design characteristics may not be characteristic of other parts of the electric power system Province-wide. To that end, we applied a modified TBL process that extended the normally anticipated application of the PIEVC TBL module in order to gain a preliminary understanding of the TBL implications of adopting, in other regions of the Province, some of the features of the main case study area that lead to its resiliency.

In this study, for the reasons outlined above, the PIEVC TBL was not used. In its place, we applied a modified WDA approach. In most cases, WDA is used to select one alternative to directly address a specific need, such as selecting the design option that best addresses all criteria for a specific application (e.g. options for building redundancy in locations served by a single circuit). In our case, the process was used to establish the relative merit of implementing, for other segments of the Ontario Transmission System, those features that make the main case study area generally resilient to the changing climate parameters. In essence, the question we are posing with this range of alternatives is:

Of the options considered, which will best provide enhanced system resiliency based on an analysis of social, environmental and economic factors?

In this approach, the decision-maker is provided with a prioritized list of options, based on a specified set of criteria. This methodology is intended to establish project sequencing over a number of years, allowing for the periodic re-evaluation of criteria to ensure they continue to reflect the overall objectives and priorities of the organization. The methodology may also be used to prioritize concepts that require further research and analysis.

Our process included hosting a workshop with transmission system experts to:

- Clearly define the elements of the transmission system in the Toronto region that support the identified climate change resiliency;
- Identify several locations within the Province where such features may not prevail;[21]
- Identify order of magnitude costs for incorporating the resiliency features at those less resilient locations;
- Identify potential environmental impacts associated with adopting these features at those locations, if any; and,
- Identify likely social outcomes from adopting these features, both positive and negative.

Upon completion of the workshop, the consultant team convened to review the results from the workshop and conduct a WDA of applying those features that may make the Major Transmission Station case study area more resilient than other segments of Ontario's transmission system.

7.1.2 Adjusting WDA for TBL Analysis

Normally, Weighted Decision Analysis does not contemplate different classes of "Want" criteria, such as the Social, Environmental and Economic criteria considered in a TBL analysis. Nor does it contemplate differential weighting across these categories of Want criteria with respect to the influence they have on overall ranking of the alternatives being considered. To accommodate these nuances, we modified the Weighted Decision Analysis in two key areas.

7.1.2.1 Provision for Modifying Emphasis Placed on TBL Categories

In our analysis we identified a number of Want criteria specifically related to the three TBL categories:

- Social;
- Environmental; and,

[21] These were initially informed by the case study options considered in the first WDA.

- Economic.

Furthermore, we allowed workshop participants to guide the relative weighting placed on these categories. Initially, we suggested equal weighting for each category of Want criteria. However, at the workshop the expert participants emphasized that equivalent emphasis does *not* reflect the way the decision-maker typically considers these factors. They suggested that a more reasonable reflection of the "real world" would be:

- Social – 5%
- Environmental – 5%
- Economic – 90%.

They also suggested considering scenarios placing greater emphasis on social and environmental elements of the TBL and less emphasis on economics. To this end, we considered the 90% economic case our baseline and evaluated the impact of varying the weighting of Want criteria to establish the impact on the final outcomes, as presented in Table 5.

Table 5. TBL Scenarios.

Scenario	TBL Emphasis (%)		
	Economic	Social	Environment
90	90	5	5
80	80	10	10
70	70	15	15
60	60	20	20
50	50	25	25
40	40	30	30
30	30	35	35

7.1.2.2Modifications to Ensure Equality of TBL Categories

The other adjustment necessary to the standard Weighted Decision Analysis process was necessitated by the consideration of separate Social, Environmental and Economic factor categories. We needed to ensure that the total weighted Want criteria scores for each category are equivalent. That is, without the adjustments outlined above, the analysis does not artificially overemphasize one Want criteria category over the others. This can happen if the total score for one category is greater than the total score for the others. To address this, we adjusted the total score for each of the Want categories to 100 points. This was achieved by calibrating the resulting values to a 100-point scale.

When these two adjustments are applied, the maximum possible score for any given alternative is 100 points.

7.2 Applying the Methodology

7.2.1 Alternatives Considered

Of the six adaptation alternatives considered (Table 6) the first five were based on infrastructure features identified as conferring severe weather- and climate change-related resiliency from the Major Transmission Station case study area. Workshop participants identified Alternative 6, local generation at Pickle Lake, as a good example to consider as a means of enhancing the resiliency of a remote community to changing climate conditions.

Table 6. Alternatives.

Alternative	Description
1	Northern community supplied by single circuit 115 kV line Twinning - Redundant Design
2	Northern community supplied by single circuit 115 kV line Enhanced Design - Asset Hardening.
3	Northern community supplied by single circuit 115 kV line Low Voltage Redirection
4	500 kV transmission corridor carrying supply from major nuclear facility Asset Hardening
5	Northern communities supplied by 115 kV transmission Twinning - Redundant Design
6	Northern communities supplied by 115 kV transmission Local Generation

The six alternatives in Table 6 represent 3 different transmission grid segments. The various northern community 115 kV lines represent electrical transmission circuits servicing physically isolated rural locations in the northwestern part of the province, characterized by a single circuit up to several hundred kilometers in length. These circuits are also supported, for the most part, by wood pole type support structures, possibly further increasing vulnerability to climatic loading. Hence, adaptation options for these locations focus on multiple options which would increase system *redundancy*. The third segment, the 500 kV line corridor, represents a transmission corridor linking a major source of power generation to populated load centres (in southern Ontario). The corridor is located in a portion of the province known to be susceptible to extreme climatic events, particularly ice storms and tornadoes, of even greater intensity than those experienced in the immediate vicinity of the GTA. Given the enhanced risk of high impact localized events (in contrast to the main case study Transmission Station) and the fact that redundancy characteristics are already present (multiple circuits, capacity for low-voltage redirection, etc.), the focus of adaptation options for the 500 kV corridor is on *asset hardening*.

The WDA criteria used for this analysis are outlined in Table 7.

Table 7. WDA Criteria - Base Criteria.

	Description	
	Must	
M1	Be technically feasible	
M2	Be sustainable in the long haul	
M3	Meet all current design standards	
M4	Have clear cost accountability	
M5	Be acceptable to the customer	
M6	Have clear stakeholder buy in	
	Wants	**Weight**
	Social Factors	**5.0%**
S1	Address community needs	**10**
S2	Enhance system reliably for remote communities	**9**
S3	Provide additional power to support new community growth.	**5**
S4	Not be aesthetically displeasing	**4**
	Environmental Factors	**5.0%**
EN1	Minimize environmental footprint	**10**
EN2	Not increase EMF exposure to vulnerable stakeholders	**8**
EN3	In existing ROW – Minimize greenfield development	**6**
	Economic Factors	**90.0%**
EC1	Minimize incremental cost	**10**
EC2	Within anticipated development budgets for the infrastructure owner	**9**
EC3	Minimize increases in annual operations and maintenance budgets	**8**

7.2.2 Workshop

The TBL workshop was conducted on March 2, 2015. During the workshop participants reviewed a preliminary WDA analysis and provided guidance on the approach, the scoring and the overall weighting of Economic, Social and Environmental criteria. Based on input from the experts at the workshop, subsequent to the workshop new parameters were added to the analysis and scoring was adjusted. The experts indicated that these criteria and weightings were generally consistent with the way the regulator conducts their decision-making processes.

7.3 Results

The analysis resulted in a range of global WDA scores covering the entire scope of the assessment and provided a picture of how adjusting economic, social and environmental emphasis in the analysis can affect the overall priority ultimately assigned to an alternative.

Table 8 presents the numerical results.

Table 8. TBL Scores for each scenario.

		TBL Score (Maximum = 100 points)					
		Alternative					
		1	2	3	4	5	6
Scenario % Economic Emphasis	90%	21	70	76	83	21	46
	80%	27	72	77	82	27	49
	70%	32	73	77	81	32	52
	60%	37	75	78	80	37	56
	50%	42	76	78	79	42	59
	40%	47	78	79	78	47	62
	30%	52	79	79	78	52	66

Legend

- First Priority (4 at 90%–50%; 3 at 40%; 2 and 3 at 30%)
- Medium Priority
- No Go

The WDA scores indicate that **Alternatives 1, 5 and 6** do not merit immediate attention, driven mainly by the high weight assigned "economic" considerations and the relatively high cost of each of these options. Meanwhile, across the entire range of economic weighting scenarios asset hardening alternatives scored relatively high. When economic factors were most heavily weighted, **Alternative 4**, asset hardening in the 500 kV corridor (linking major generation to load centres) scored highest, with **alternatives 2 and 3,** enhancing design in the northwest Ontario region (long single circuit lines supplying rural communities), scoring only modestly lower. As emphasis on economic factors was reduced, options for asset hardening in the northwest Ontario region became even more competitive with work on the 500 kV Corridor.

Figure 2 depicts these dynamics.

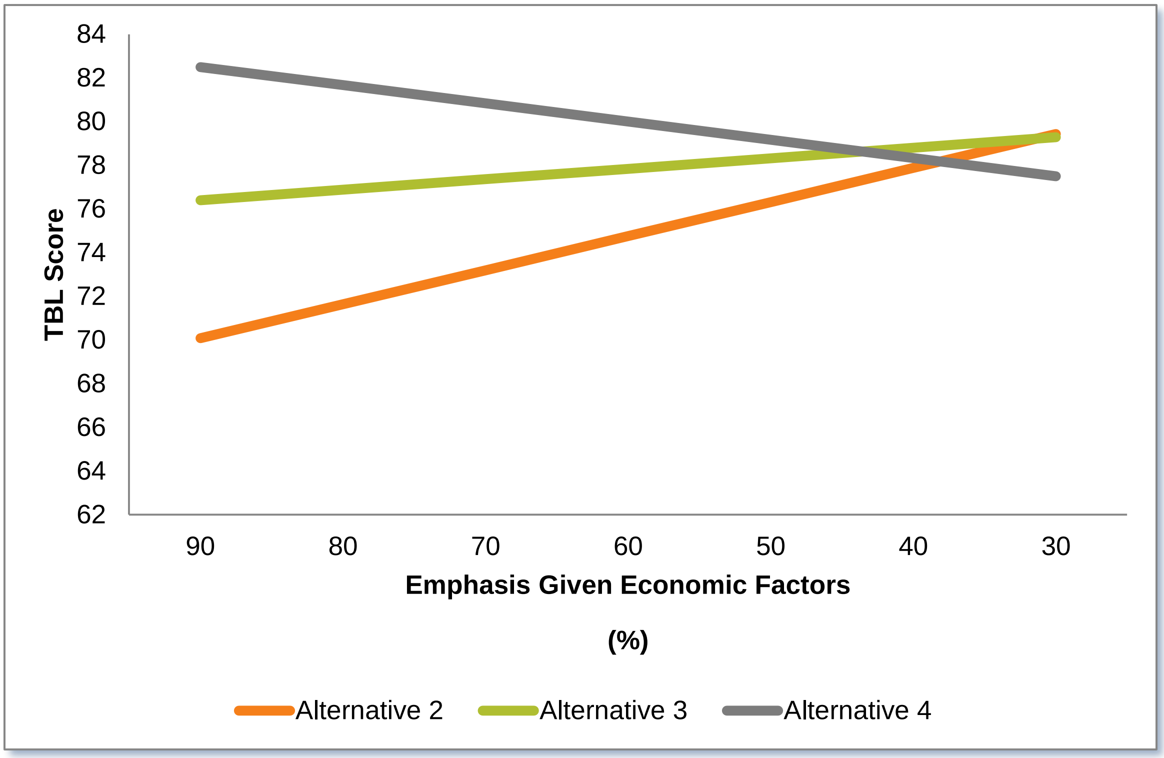

Figure 2. TBL Sensitivity Analysis. Adjusting Economic Emphasis for Alternatives 2, 3 and 4.

There are several insights to be gained from this analysis. First, these three alternatives do not cover a wide range of WDA scores, and given the “order of magnitude” approach of the analysis, the scores are close enough to be considered nearly equivalent. The scores become even closer as economic factors are deemphasized and more weight is given to social and environmental factors.

Second, the slightly higher priority for work in the 500 kV corridor was consistent until economic factors were scored below 40%. This gives us confidence that the overall priority, based on the factors considered in this WDA analysis, should be given to asset hardening in the transmission corridor linking this major source of generation to populated load centres in southern Ontario, and somewhat less priority to asset hardening in the northwest Ontario region.

Third, these results are driven primarily by population density and the impact that this has on the social dynamic of the WDA analysis. Simply stated, improving climate change resiliency in the case of the transmission corridor in southern Ontario provides benefits to a much larger segment of Ontario’s population.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Overall Conclusions

8.1.1 The Transmission System in the GTA is Generally Resilient to Changing Climate

The study found that the electric power system in the Toronto region is generally resilient to the climate conditions considered in this analysis over the time horizon of the assessment. Our analysis identified only four high risks out of the 1,053 total climate-infrastructure interactions considered (< 0.4%), over the time horizon of this assessment. However, we did note patterns of medium risk associated with climatic events that cover wide geographic areas within the region, including:

- Ice storms; and,
- High winds associated with convective storm events.

These events could have potentially broad ranging impacts on a variety of infrastructure components and result in widespread system interruptions. While these events are relatively rare, and analyses of both historical and future trends contain significant uncertainties, they can and have resulted in significant service interruptions in the past.

8.1.2 The 500 kV System is More Resilient than the 230 kV System

We noted that the 500 kV System is relatively more resilient to changing climate than the 230 kV System. This is not surprising since higher voltage systems are typically designed to more robust standards than are lower voltage systems. This does not imply that the 230 kV Systems are problematically vulnerable, but rather that under extreme conditions of ice accretion and high winds the 230 kV elements of the overall system will in most cases fail before those of the 500 kV System.

8.1.3 Potential Interaction of Transmission Infrastructure with Transportation Corridors

We noted an area of high risk associated with transmission lines crossing transportation corridors. Under the temperature profiles anticipated over the time horizon of this assessment, workshop participants raised concerns over transmission lines potentially contacting vehicles. While temperature related line sag has not yet been observed in Ontario, it is worthy of further monitoring and evaluation. In contrast to localized extreme events, confidence is very high in projections of extreme high temperatures, with all climate models and all temperature related parameters considered in this assessment indicating significant increases in probability of occurrence. These projections are also very consistent with recent and historical observations and associated trends, including the apparent non-linear (possibly *exponential*) increase in temperatures in recent observations. Hence, the only significant uncertainty remaining with this risk is a lack of infrastructure data describing the height of wires above transportation corridors.

8.2 Overall Recommendations

8.2.1 Lessons Learned from Eecution of Study

One of the goals of study was to inform next steps toward a more comprehensive assessment applied to other parts of Ontario's electrical system, and elsewhere in Canada. Some lessons learned in the course of this project that, if addressed, could aid in the transferability of the approach.

The knowledge of industry experts regarding not only the physical characteristics of the infrastructure, but how infrastructure systems operate in practice, is paramount for understanding climate vulnerabilities. Over the course of several workshops and meetings with transmission experts and planners, it became apparent that there is a wealth of information related to the historical design and performance of the electric power system that resides within the knowledge base of the industry practitioners, and which may not necessarily be reflected in existing documentation such as diagrams or reports. Some of this information included particular knowledge about the design specification of certain components within the system, and in some cases recollection of the rationale for why the infrastructure was built in a certain way. In other cases, this information includes recollection of how the power system was recovered or restored following past emergencies. This type of information is critical to the outcome of a vulnerability study, and the lesson to be learned for future assessments is to ensure that the study team includes, or consults with, experts with a long history of knowledge about the design and performance of the system being assessed.

As mentioned elsewhere in this report, there is a high degree of security that applies to information related to critical assets making up the electric power system, to protect the system from malicious attacks or cyber-security threats. This level of security can be an impediment to completing climate vulnerability studies, since it is important to be able to discuss freely the nature of the infrastructure being assessed while also consulting in the relevant experts (i.e. climate and vulnerability assessment members of the consulting team). Future studies should ensure that adequate non-disclosure agreements are ready and signed by participants at the outset of a project, keeping in mind the NERC requirements for disclosing information on critical electric power system infrastructure that is not "need to know," but still allowing for the free flow of infrastructure information needed to properly execute a vulnerability assessment.

8.2.2 System Wide Adaptation Options

The resiliency inherent to the electric power system's design can largely be attributed to stringent reliability standards that were developed in North America following a major blackout that occurred in 1965. Unlike other infrastructure sectors, the electric power system is required to be designed to provide a minimum level of load security, achieved largely through system redundancy, which allows for the infrastructure to continue operating with relative integrity, even when certain critical components are taken out of service. Despite this, there are additional adaptation options that can be considered.

Where asset “hardening” is deemed an appropriate measure for increasing the breaking threshold of individual elements of the infrastructure system (e.g. older infrastructure nearing end-of-life, or for lower voltage infrastructure built to a lesser design standard), plans can be developed for increasing the design thresholds at times that are coincident with refurbishment and/or end-of-life replacement (as opposed to replacing like-for-like). This approach can lessen the total cost of asset hardening by reducing it to an incremental measure.

Integrate foreseeable extreme climate events into electric power system emergency preparedness and response scenarios, including training for system operators and field crews. In addition, closer coordination with agencies responsible for other critical infrastructure systems whose integrity can impact the ability of power system personnel to respond to emergencies (e.g. transportation and telecommunications) can help in timely and effective response overall. For example, coordinated plans and procedures can help to ensure that field crews can access locations quickly to make repairs and restore power, and remain in communication during the course of a system emergency.

System operators and asset owners should further investigate the potential benefits of demand side management and customer-based generation resources. These can act as an effective means of reducing customer vulnerability to grid interruptions following extreme weather events. Certain types of demand side management can reduce the overall electric demand on power system infrastructure and reduce the total customer load at risk if an interruption occurs. Furthermore, reducing the demand on infrastructure means that equipment temperatures may be cooler and thus be less susceptible to certain types of failure under heat stress. Customer-based generation, if configured to run in an “island” mode or as an islanded micro-grid, can allow customers to remain with power even if the grid fails. The customer benefits of these types of resources were demonstrated during the Hurricane Sandy incident in New York City, where some customers that had recently installed combined heat and power distributed energy systems remained supplied in the absence of grid supply.

8.2.3 Monitor Frequency of Ice Storm Events

Based on our analysis, ice storm events leading to significant levels of ice accretion are somewhat likely to highly unlikely during the period of assessment, depending on the threshold in question, with probabilities of occurrence in the 20-30% range for the lowest (24 mm radial ice accretion) threshold, to as low as ~1% for the most extreme cases (50 mm events). However, given the system wide impacts associated with these events, especially on the 230 kV system, we recommend ongoing monitoring and re-evaluation of the likelihood of these events. Climate projections of future ice storm conditions should be updated regularly based on the most up-to-date climate science and meteorological observations. If either or both empirical observations and/or improved climate projections provide stronger indications that frequency is or could be increasing even more rapidly than current estimates suggest (Cheng *et. al*. 2007), the overall level of risk associated with these events will increase accordingly and may merit direct engineering intervention.

When compared to other extreme event types, ensemble climate projections of ice storm conditions in southern Ontario (Cheng *et. al*. 2007) tend to be more robust (i.e. tend to produce far less "spread" between model results) than other high impact weather events. However, these projections still contain significant levels of uncertainty, particularly for the most extreme cases. This is again mainly rooted in a lack of high quality historical observations to inform both empirical analyses of historical trends and for the calibration of future projections. Indications from Cheng *et. al*. (2007) and other studies (e.g. Kunkel *et. al*. 2013) indicate that the most extreme events will indeed increase more rapidly in frequency than events of lesser severity. However, the magnitude of these changes remains unknown, hence the potential benefit of improved monitoring, coupled with further research to inform any eventual adaptation actions.

8.2.4 Monitor Frequency and Impact of High Wind Events

Our analysis suggests potential system-wide impacts associated with high wind events caused by convective storms. The 230 kV System appears to be somewhat more vulnerable to these events. Climate projections for conditions associated with high wind events should be updated regularly based on the most up-to-date climate science and meteorological observation.

Severe thunderstorm winds are small scale events and, as discussed, changes in intensity or frequency for this class of event are much more difficult to detect or project. As with extreme ice storms, continued monitoring and recording of these events is critical to understanding future trends and, in turn, future changes in *risk* which may arise. These also require specialized data collection methods and associated training for proper monitoring, well beyond additional passive instrumented climate monitoring. These techniques include methods such as post-event forensic investigation of failures, and targeted historical research to identify and classify important past events to improve the historical record of thunderstorm winds and their impact on electrical transmission systems.

If, through these continued observations, the frequency is observed to be increasing, the overall level of risk associated with these events will increase accordingly and may merit direct engineering intervention.

8.2.5 Survey Transmission System – Transportation System Crossings

The assessment identified potentially high-risk scenarios associated with high temperatures causing line sag sufficient to allow contact with vehicles in transportation corridors. This scenario was speculative in nature, as these events have not been observed in Ontario. Given the lack of data associated with specific line elevations over transportation corridors the assessment team was unable to resolve the magnitude of these risks within the scope of the current assessment. Based on this we recommend that the infrastructure owner:

- Survey locations where transmission systems cross transportation corridors;
- Assess line elevations above the corridor; and,
- Determine if line sag under the temperature profiles projected over the time horizon of the assessment could in fact result in contact with vehicles.

8.2.6 Conduct Additional Forensic Analysis of Four-Wire Bundles

We also identified lack of information regarding the performance of four-wire conductor bundles as a potential limitation in this assessment. Four-wire conductor bundles are a characteristic of the 500 kV transmission lines in Ontario. We recommend further forensic analysis of the performance of four-wire bundles under the ice accretion and high wind loading. Results from this additional analysis could be integrated into the vulnerability assessment to determine if the projected risk profiles were overly conservative based on the team's assumptions in this regard. The analysis might consider the performance of four-bundle conductors in other regions of North America where failures have been observed. Such analysis would improve the overall veracity of future climate change risk assessments on the electric power system.

8.3 Important Conclusions by Section

8.3.1 Climate Analysis

8.3.1.1 Extreme, Small Scale Events Were Key Climate Parameters

Inherently robust engineering within the infrastructure system led to the most prominent patterns of risk being associated with the most extreme climatic events (i.e. high wind events, extreme ice accretion). This is consistent with initial project scoping and consultation results, as practitioners and asset managers consistently demonstrated most interest in "low probability-high impact" events. However, these results also highlight a number of challenges associated with risk assessments addressing this class of meteorological phenomena, both in terms of historical analyses and future projections:

- The nature of most of the small scale, localized extreme events contemplated in this assessment leads to significant uncertainty when determining probability of interactions with infrastructure; i.e. while empirically based estimates of their occurrence are available, the "true" frequency of extreme events remains unknown[22] as these are, by their very nature, infrequent and localized in their impacts; and,

[22] In contrast to much more frequent climate parameters which are recorded at climate stations, extreme localized and/or rare events such as tornadoes, downbursts, extreme ice storm, etc., have required the application of

- These types of small-scale extreme events are also difficult or impossible to asses using climate change projections, including both dynamical and statistical downscaling techniques.

Results from downscaled climate projection studies (e.g. Cheng *et. al*. 2007, 2012) as well as analyses of historical observations (e.g. Kunkel *et. al*. 2013) are generally consistent in indicating greater increases in frequency for higher magnitude events relative to events of lower magnitude. For example, the frequency of 90 km/h wind gusts appears to increasing more rapidly than for 70 km/h gusts (Cheng *et. al*. 2012); however, a continued dearth in baseline historical observations of extremes introduces far greater uncertainty in empirical analyses and future projections than exists for events of lesser magnitude.

8.3.1.2 Practitioner Consultation Played a Critical Role in Focusing the Assessment

Practitioner consultation played a particularly important role in risk ranking for specific climate parameters in this assessment.

- This led to an overall decrease in the number of climate elements considered in the assessment.
- The project team had initially assumed, mainly due to the literature review and past experience with electrical *distribution* infrastructure, that extreme high temperatures posed a significant and important direct risk to electrical transmission infrastructure; however, practitioners in turn indicated that this was not the case, even when considering future projections in extreme heat related loading.

8.3.1.3 A Lack of Representative Climate Restricted the Assessment

Although located in a densely populated area, the case study needed to rely upon historical climate data recorded several dozen kilometers distant and in slightly different geographical settings, meaning the data were not ideally representative of site conditions.

- Data from observational sites physically closer to the case study site were of lesser quality, mainly due to:
    - Lack of coverage of key parameters of interest (e.g. wind gusts, ice accretion amounts); and,
    - relatively brief periods of record (when compared to other more distant observational sites).

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specialized data collection techniques (e.g. historical newspaper archive searches, forensic post-storm investigations) to record historical data of sufficient detail and quality for even the most **basic** of empirical analyses such as frequency, spatial extent.

8.3.2 Triple Bottom Line Adaptation Analysis

8.3.2.1 TBL is a Useful Tool

Even at the high level of analysis used for the TBL process adopted for this study conclusions can be drawn which may be useful for decision-making. For example, based on the factors considered, the current focus on investment in the Toronto region (i.e. 500 kV corridors critical for supplying large populated centres) was supported by TBL analysis, consistently across all of the scenarios considered. Furthermore, it was identified that asset hardening in more rural or remote regions may also be beneficial, and given appropriate emphasis on social factors, these actions may be as justifiable as doing additional work in the more populated regions of the province.

8.4 Important Recommendations by Section

8.4.1 Need for more Long-Term Historical Data

The availability of long-term historical climate data within the immediate vicinity of the case study should be increased.

- Observational data should be expanded to include climatic conditions directly relevant to important climate parameters for electrical transmission infrastructure, specifically;
    - Measurement of extreme wind gusts; and,
    - Measurement of ice accretion and associated causes/conditions (e.g. freezing rain, fog).

Damage and failure data held by IESO, Hydro One and other asset owners could be incorporated into forensic investigations of past incidents and the information made available to the appropriate stakeholders (e.g., the research community, policy-makers, regulators, etc.). While this project did not have adequate scope/time to execute multiple forensic investigations, similar investigations for the “sister” Toronto Hydro distribution project resulted in several important findings relating to climate related “breaking thresholds” (i.e. actual climate thresholds developed through analysis of in-field performance).

- Such studies could better define the structural limits, and the specific *causes* of failures and underperformance, particularly when combined with additional observations (meteorological data) and information (e.g. descriptions of impacts to adjacent infrastructure, buildings, etc.); and,
- Post-event investigation could be formalized to include training and informational materials regarding relevant climatic and weather events, and could also be conducted in collaboration with other agencies such as Environment Canada.[23]

[23] In one instance relating to a tornado related failure of multiple steel lattice support towers along a portion of a 230 kV circuit in southern Ontario, an engineering practitioner is known to have contacted the meteorologist who

An assessment of important climate parameters should be expanded if and/or when additional information on the nature of some infrastructure elements of the case study become available, specifically relating to infrastructure data which were not made available for the current study. Specifically, the identification and assessment of:

- Any below-grade infrastructure which may or may not be susceptible to overland/extreme rainfall related flooding;
- Overhead clearance/heights and expected temperature related sag of electrical lines crossing transportation corridors; and,
- Performance of 500 kV four-bundles under ice accretion and/or extreme wind loading.

Having identified extreme, localized, short duration weather events as posing the greatest risk of the climate events studied, it is recommended that electric industry stakeholders (including asset owners and planners) review and expand monitoring and response planning for these types of events.

- Because the weather conditions resulting in the occurrence of such extreme events as EF2+ tornadoes and ice storms capable of producing 60 mm or greater ice accretion are relatively well understood it is possible to provide relatively “skillful” forecasts hours to days prior to such events (e.g. similar to current severe weather watches and warnings, but more advanced, specialized and tailored to the electrical infrastructure); and,
- In a similar vein, advisories relating to line sag from extreme heat or ice accretion, and associated hazards for transportation corridors, if applicable, could be developed, again making use of current knowledge relating to weather forecasting and extreme events.

Using currently available data and techniques, such as historical analyses of extreme events and climate change downscaling studies, understanding the probability of occurrence (including potential future changes) of extreme events can be improved with further study:

- Specialized return period analyses and climate change downscaling studies for extreme thunderstorm winds should be conducted to better inform both engineering and/or emergency planning. These would include the combination and comparison of existing historical data sets (e.g. National Tornado Database, Sills *et. al*. 2012), coupled with in-house impacts information.
- Specialized return period analyses and climate change downscaling studies for extreme ice accretion events, particularly for more severe thresholds (e.g. 50 mm) identified in this assessment, are also indicated. These could be coupled with additional research on the “true” impacts of such extreme ice accretion events, such as detailed historical research assessing the impacts of events of similar magnitude in adjacent jurisdictions (e.g. New York) which have experienced much more severe ice storms than have been

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had conducted the post-event forensic assessment and dispute the finding that a tornado was responsible for the damage. These types of disagreements are indicative of a *clear* lack of interdisciplinary knowledge, as well as a lack of training in recognizing the characteristics of climate and weather impacts on the electrical transmission system.

recorded in Ontario, but which could provide indications of the effects of such an event *were it to occur*.

8.4.2 Conduct TBL Analysis of Asset Hardening

Based on the limitations of the TBL analysis, we are unable to provide recommendations regarding specific adaptation options. However, the high level TBL analysis did suggest that asset hardening might be beneficial in both the Toronto region and in more remote locations. Based on this we recommend that the IESO conduct a detailed analysis of asset hardening as a means of improving climate change resiliency of the Ontario Power Transmission System in both urban and more rural and remote locations.

9. LIMITATIONS OF THE STUDY

9.1.1 Four-Wire Bundles (500 kV System)

The assessment team was not able to acquire data on the performance of the four-wire bundles used for 500 kV Systems. We noted a lack of forensic evidence regarding how these components perform in various weather scenarios. For the purposes of this assessment we treated these four-wire bundles the same as single-wire conductors used in 230 kV transmission systems. We believe that this is a conservative assumption, but given the lack of supporting data, this aspect of the assessment is less robust.

9.1.2 No Site Visit

The assessment team was unable to conduct a site visit to physically evaluate civil infrastructure elements in the transmission stations. This was due to security concerns associated with the critical nature of these systems and strict safety protocols concerning live electrical equipment. The team therefore used publically available information and information provided by the planners and asset owners to identify these components for the assessment.