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April 30, 2020

Board of Commissioners of Public Utilities
Prince Charles Building
120 Torbay Road, P.O. Box 21040
St. John's, NL A1A 5B2

Attention: Ms. Cheryl Blundon
Director of Corporate Services & Board Secretary

Dear Ms. Blundon:

Re: Reliability and Resource Adequacy Study Review - Assessment of As-Designed Capacity of the Labrador-Island Link

Please find attached the Structural Capacity Assessment of the Labrador Island Transmission Link[1] prepared by EFLA Consulting Engineers ("EFLA"). This assessment was completed to provide further understanding of the strengths and vulnerabilities of the overhead transmission component of the Labrador-Island Link ("LIL") with respect to wind and glaze ice combinations. The assessment is benchmarked against the 50, 150, and 500-year return period loadings as outlined in the CSA-C22.3 No 60826 Design Criteria of Overhead Transmission Lines standard for line design in Canada.

The assessment by EFLA addresses the following:

- What is the "as-designed" structural capacity with respect to CSA requirements?
- Which sections have the lowest structural capacity concerning CSA requirements?, and
- Which components in the LIL line are critical concerning the structural models used?

Not surprisingly, there are differences between this expert information and previous expert information provided to the Board of Commissioners of Public Utilities ("Board").[2] Newfoundland and Labrador Hydro ("Hydro") notes the observed discrepancies between the expert reports will be examined carefully considering the individual load case results, as well as the assumptions used by each expert consultant, so that the basis for the discrepancies will be understood and ultimately considered in the line reliability assessment.

The assessment completed by EFLA is the first component of Hydro's overall assessment of the reliability of the LIL. EFLA's report will be used together with the Assessment of LIL Reliability in Consideration of Climatological Loads, currently underway by Halder & Associates Ltd., to inform Hydro's probabilistic failure analysis in determining overall line reliability. The outcomes of this analysis will be reflected in Hydro's Reliability and Resource Adequacy Study 2020 Update, which is scheduled for filing with the Board on November 15, 2020.

Should you have any questions, please contact the undersigned.

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[1] Referenced in Hydro's previous correspondence as the "Assessment of As-Designed Capacity of the Labrador-Island Link."
[2] Investigation and Hearing into Supply Issues and Power Outages on the Island Interconnected System, Hydro's response to Request for Information NP-NLH-004.

Yours truly,

NEWFOUNDLAND AND LABRADOR HYDRO

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STRUCTURAL CAPACITY ASSESSMENT OF THE LABRADOR ISLAND TRANSMISSION LINK (LITL)

28.04.2020

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Labrador Island Transmission Link

PROJECT MANAGER – CLIENT REPRESENT.

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CLIENT

Newfoundland and Labrador Hydro

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SUMMARY

A strength capacity assessment of the Labrador Island Transmission Link (LITL) was conducted to determine the capacity of the "as-designed" line concerning requirements in the CAN/CSA C22.3 No. 60826-10 [1] (herein referred to as CSA) under wind and/or glaze ice load conditions. Rime ice condition is not considered in this study and will be considered as a separate study in the next phase.

Climate load values for the design of the LITL were developed following the principles outlined in CSA considering identified operational risks and special studies. The design exceeded some of the basic requirements in the standard.

The assessment here uses design models that the designers, SNC-Lavalin, prepared to evaluate the performance of the line against the loading specified in CSA with different return periods. The goal was to use loading specified in the CSA standard without a special study of local conditions. It was specified in the project that underlying assumptions, used in the design, should be kept as far as they complied with the design standard. It is not part of the study to review or verify the PLS-Cadd and PLS-Tower models made by the designers.

When evaluating the overall capacity of the LITL, the utilization of individual components is not equally important due to failure sequencing which is controlled by varying the selection of the component strength factors[1]. The suspension towers are defined in the design requirements as the most critical component in the LITL with the lowest safety factors (e.g. 10% lower strength factor than the tension towers), hence they should be the first to fail.

The study concludes that overall, the LITL fulfills the CSA-50 loading and is close to fulfilling the CSA-150 loading with the following exceptions:

- Eight suspension towers have utilization exceedance up to 4% in zone 3a and zone 11-4 with "*Wind and Ice*" loading. The ice loading for these towers was conservatively assessed with the same approach as the design of the LITL with same radial ice applied to the conductors and tower members. When the ice load is reduced to CSA recommendations, that are more realistic, the utilization exceedance is up to 0.8% for three towers. This is not considered critical.
- The OPGW conductor has utilization exceedance up to 9% in the load case "*Ice and Wind*" in zones 3b, 4a, 4b, 6 and 10. The maximum utilization in the study was set at the damage limit of 80% of RTS. The increased utilization may lead to permanent elongation of the OPGW, however it is within the failure limit and should not break or result in a line outage. It may therefore be possible to accept a higher utilization value in few spans provided it is well below

[1] Strength factor is the inverse of safety factor.

the failure limit[2]. The strength capacity corresponds to approximately 90 years return period of loading.

- The electrode conductor suspension hardware fulfills a safety factor is 1.88 instead of 2. The specified safety factor of 2 is considered high compared to normal design practice. This only presents a marginal increase in the risk of failure.

The above-mentioned exceptions will be considered in more detail in the overall reliability study of the LITL.

[2] The OPGW has been successfully type tested to 109% of rated tensile strength, however this value is not guaranteed by the manufacturer.

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ABBREVIATIONS

CSA	Refers here to CAN/CSA-C22.3 No. 60826-10
CSA-50	50-years climatic loading according to CSA
CSA-150	150-years climatic loading according to CSA
CSA-500	500-years climatic loading according to CSA
Conductor	Conductor is here used for Pole conductor, Electrode conductor and/or OPGW
DESIGN loading	Loading used by designers in the design of the LITL
ERS:	Emergency response structure
ERP:	Emergency response plan
HOSJ:	Highlands of St-John´s
HIW:	High-Intensity Wind
HVdc:	High voltage direct current
LCP:	Lower Churchill Project
LITL:	Labrador Island Transmission Link
LRM:	Long Range Mountains
NL:	Newfoundland and Labrador
NLH:	Newfoundland and Labrador Hydro
PLS-CADD	Overhead line design program that is an “industry standard,” from Power Line Systems
PLS-Tower	Software to perform structural analysis of lattice tower, from Power Line Systems
OHTL:	Overhead transmission line
OPGW:	Optical fiber composite overhead ground wire
RTS:	Rated Tensile Strength
SOBI:	Strait-of-Belle-Isle
USCD:	Unified Specific Creepage Distance

DEFINITIONS

Reliability requirements:	Reliability requirements aim to ensure that lines can withstand the defined climatic limit loads (wind, ice, ice, and wind, with a return period T) and the loads derived from these events during the projected life cycle of the system and can provide service continuity under these conditions.
Security requirements:	Security requirements correspond to special loads and/or measures intended to reduce the risk of uncontrollable progressive (or cascading) failures that may extend well beyond an initial failure. NOTE: Some security measures, such as those providing longitudinal strength for broken conductor loads for failure containment can lead to an increase in reliability.
Safety requirements:	Safety requirements consist of special loads for which line components (mostly support members) must be designed, to ensure that construction and maintenance operations do not pose additional safety hazards to people.
Use factor:	The CSA standard uses the concept of use factor (γ_U) that is defined as the ratio of the actual load (as- designed) to the allowable load of a component. The use factor has an upper bound of 1.0 when all components are used to their full strength.
Type test:	A comprehensive set of tests used to qualify a new design to ensure minimal quality levels.
Routine test:	A set of tests used to assist in quality control during the manufacturing process

1 INTRODUCTION

This document presents an assessment of the "As-Designed" structural capacity of the Labrador Island Transmission Link (LITL)." The current study conducted by EFLA forms part of a detailed evaluation of the overall line reliability of LITL. Three tasks are identified to determine the line reliability under extreme weather conditions. These tasks are:

(1) Structural capacity assessment of the "As-Designed" strength of LITL following CSA C22.3 60826-10.

(2) Recalibration and hindcast simulations of rime icing on Long Range Mountain (LRM) and in the Southern Labrador section of the LITL. The data will be used to assess the design rime icing and combined wind and rime ice loads using the additional data that Nalcor collected from test spans.

(3) As-built capacity assessment of LITL under rime icing.

Data from these three tasks, once completed, will be used in the development of the final report titled "Reliability Assessment of LITL considering Climatological Loads."

The current report addresses task 1, the (as-designed structure strength capacity) in determining the overall reliability of LITL.

The original design of LITL here defined as "DESIGN" was based on the design principles of CAN/CSA-C22.3 No. 60826-10 (CSA), using operational experience and special studies in the determination of climatic loads. The report will provide the reader with an opportunity to become familiar with the LITL infrastructure and gain a better understanding of the strengths and vulnerabilities of the LITL overhead line system. Previously, two similar studies were conducted ([2] and [3]) to assess the "as-designed" strength of the LITL.

In this study, the authors were provided full access to design documents and design models needed for this structural capacity assessment.

1.1 Objectives

The objective of the project is to determine the "As-Designed" structural capacity of LITL considering climatic load events due to wind and glaze ice and combinations thereof. The as-designed structural capacity will be benchmarked against the 50, 150 and 500-years return period loadings provided in the CSA 60826-10 standard.

The report will answer the following:

- What is the "as-designed" structural capacity concerning CSA requirements?
- Which sections have the lowest structural capacity concerning CSA requirements?
- Which components in the LITL line are critical concerning the structural models used.

1.2 Scope

The scope of this work is limited to the assessment of the “as-designed” structural capacity of LITL with respect to CSA C22.3 60826-10 loadings. Only the ±350kV HVdc transmission line is part of the study, i.e. the electrode line on wood poles and the sea cable is excluded. The electrode line carried on the steel structures in Labrador (384 km) is considered in the study. This study report quantitatively addresses the utilization of several key line components. These include suspension towers, tension towers, foundations, pole and electrode conductors, OPGW, insulators and hardware. The work focuses on underlying assumptions made in the design of LITL and how it influences the strength capacity when using CSA defined loadings.

The evaluation of construction quality and effects of component fatigue[3] was not included nor is this study intended to review, verify, or audit the detailed engineering work undertaken in design of the LITL transmission line.

Following assumptions were used in the study:

- All wind load and glaze ice loading are strictly following CSA without considering other studies that may indicate that higher or lower loading could be more appropriate in some sections.
- Assumptions from the design of LITL were followed unless they were in conflict with the CSA Standard.
- Only load cases pertaining to reliability[4] were considered in the study.

1.3 Report Layout

The structure of this report is made up of the following parts:

- In chapter 2, a brief description is provided on the Labrador Island Transmission link (LITL).
- In chapter 3, a brief discussion of the procedure used for the analysis. This section includes the assumptions used and modifications that were made to the PLS-Cadd as-built models.
- In chapter 4, Results of the analysis
- In chapter 5, Discussion of the results
- In chapter 6, the conclusion of the study is made with recommendations for future work

[3] Such as aeolian vibration and galloping

[4] Refer to definitions.

2 THE LABRADOR ISLAND TRANSMISSION LINK (LITL)

2.1 LITL Overview

The Labrador Island Transmission Link (LITL) is a 1100km, 900 MW, 350kV HVdc transmission system. The link forms a connection between Muskrat Falls in Labrador and Soldiers Pond on the Island portion of the Province. 390 km of the line is in Labrador and approximately 700km on the island of Newfoundland. The LITL transmits power from the 824 MW Muskrat Falls hydroelectric plant to supply load on the Island. Table 1 shows the rating of the LITL and Table 2 shows the general line metrics.

FIGURE 1 The Labrador Island Transmission Link. Muskrat Falls - Soldiers Pond

TABLE 1 Rating of the LITL.

Nominal System Voltage	±350 kV HVdc
Number of poles	2
Power capacity in bi-pole mode	900 MW, 1406 A per pole
10 min overload capacity of mono-pole mode	100% (900 MW)
Continuous overload capacity in a monopole mode	50% (675 MW, 2109 A)
Peak losses on the line in bi-pole mode	92.1 MW
Peak losses on the line in monopole mode	144.4 MW
Design Voltages (Electrode lines)	± 28 kV (Labrador) ± 1 kV (Newfoundland)

TABLE 2 General Line Metrics.

Length of overhead transmission line	≈1090 km
Length in Labrador	390 km
Length in Newfoundland	700 km
Number of steel towers	3223 towers
Average steel tower height, top of the structure	40 – 45 m
Number of wood poles for electrode line	400 poles
Right-of-way (ROW)	5400 hectares
Access Roads	3300
Road Crossings	68
Transmission Line Crossings	18
Large River and Stream Crossings	402
Number of steel tower families	11
Number of culverts installed	≈3000
Length of the electrode line on steel towers	384 km
Length of the electrode line on separate wood poles	29km

The elevation of the LITL varies from sea level to approximately 630m on the top of Long Range Mountains (LRM) and 500m in the Highlands of St. John on the Great Northern Peninsula (GNP).

The Labrador section of the LITL carries two electrode conductors from the Muskrat Falls Converter Station to Forteau Point on southern Labrador. Most of the electrode line in Labrador is on the ±350 kV HVdc steel transmission towers above the Pole conductors and below the tower's single OPGW. The remaining section of the electrode line in Labrador is supported on Wood Pole Structures. There is a short section of the electrode line on wood pole structures between Soldiers Pond and Dowdens point in Newfoundland.

2.2 Climatic loading in the LITL

Under the DESIGN case, The LITL was divided into eleven separate main loading zones[5], see Figure 2, concerning wind, ice and coastal exposures. The tower and foundation types have been designed and to suit the different loading zones. Detailed information on each loading zone section is in Table 3.

[5] This study uses 21 loading zones in order to cover loading zones in CSA more accurately.

FIGURE 2 LITL Transmission Route and Meteorological Zones.

TABLE 3 Brief description of each loading zone section of LITL.

ZONE		DESCRIPTION	LENGTH	ELECTRODE *	HEIGHT RANGE A.S.L.			USCD	TOWER NUMER (FINAL)	
					Min.	Aver.	Max.		Start	End
			(km)		(m)	(m)	(m)	(mm/kV)	(num.)	
Labrador	1	Av. Zone 1	272.3	Y	18	389	551	37	1	750
	2a	Labrad. High Alp.	12.3	Y	337	384	423	37	750	802
	2b	Labrad. Extr. Alp.	63.1	Y	319	376	432	37	802	1110
	2c	Labrad. High Alp.	22.1	Y	224	282	346	37	1110	1209
	3a	Average Zone 2	12.4	Y	209	257	300	37	1209	1246
	3b	Average Zone 2	13.1		15	122	224	58	1246	Gantry
Newfoundland	4b	Average Zone 2	12.8		13	27	40	58	1283	1316
	4a	Average Zone 2	56.2		39	121	279	37	1316	1457
	5	HOSJ High	18.9		250	373	499	37	1457	1529
	6	Average Zone 2	70.1		48	129	373	37	1529	1703
	7a	LRM High Alpine	23.2		389	476	533	37	1703	1806
	7b	LRM Extreme Alpine	8.1		526	559	606	37	1806	1846
	7c	LRM High Alpine	12.9		371	481	587	37	1846	1900
	8a	Average Zone 2	12.9		402	487	539	37	1900	1935
	8b	Average Zone 1	74.6		90	260	483	37	1935	2122
	9	Alpine	7.8		245	374	494	37	2122	2145
	10	Average Zone 1	221		35	40	302	37	2145	2671
	11a	Eastern Zone	177		15	123	278	37	2671	3047
	11b	Eastern Zone						58	3047	3223

* Given as "Y"= yes if electrode line is on the steel tower in the section

2.3 Towers

The tower family for the Labrador-Island Transmission Link includes 11 different tower types: A1, A2, A3, A4, B1, B2, C1, C2, D1, D2, and E1. Tower families A and B are suspension towers and families C; D and E are tension towers. Figure 3 and Figure 4 show general arrangement of the guyed and self-supporting towers used on the line.

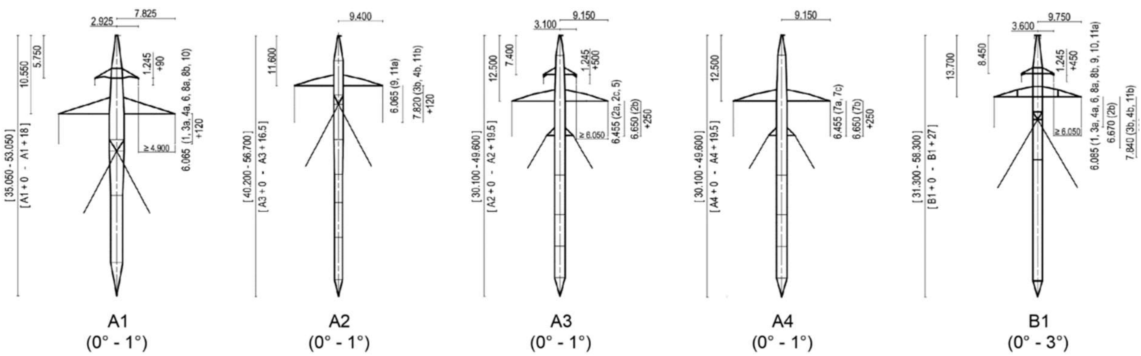

FIGURE 3 Tower geometries for guyed towers.

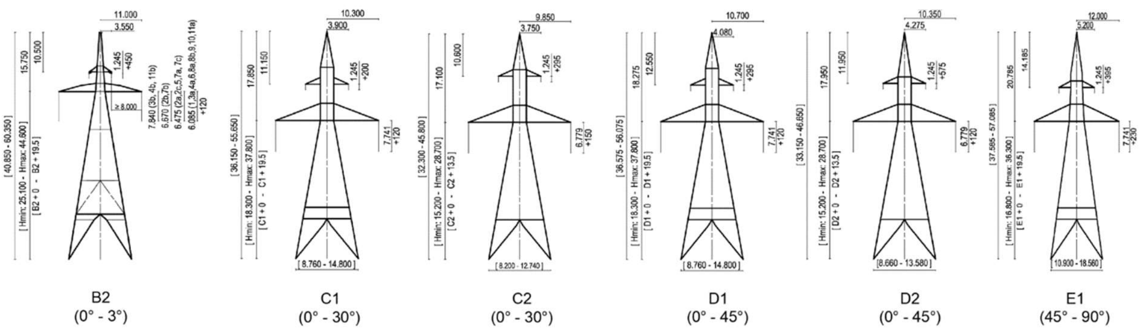

FIGURE 4 Tower geometries for self-supporting towers.

Figure 5 and Figure 6 show the general arrangement of tower families C, D and E. Figure 7 and Figure 8 show the general arrangement of tower families C, D and E.

FIGURE 5 1st tower in LITL installed in April 2015.

FIGURE 6 Suspension tower without electrode lines

FIGURE 7 Tension tower without electrode lines

FIGURE 8 Tension tower without electrode lines

TABLE 4 Basic information for tower types

TOWER TYPE	DEFLECTION ANGLE LIMIT (DEG)	HEIGHT RANGE TO		WEIGHT RANGE (TON)	WITH ELECTRODE ATTACHMENT
		bottom cross-arms (m)	OPGW attachment (m)		
A1	0 – 1	24.5 – 42.5	35.1 - 53.1	6.5 – 8.1	Yes
A2	0 – 1	17.6 – 37.1	30.1 - 49.6	9.4 – 12.6	Yes
A3	0 – 1	28.6 – 45.1	40.2 - 56.7	8.5 – 10.3	No
A4	0 – 1	17.6 – 37.1	30.1 - 49.6	9.3 – 12.5	No
B1	0 – 3	17.4 – 44.4	31.4 - 58.4	12.2 – 18.3	Yes
B2	0 – 3	24.9 – 44.4	40.7 - 60.2	16.9 – 32.1	Yes
C1	0 - 30	18.3 – 37.8	36.2 - 55.7	Max. 31.8	Yes
C2	0 - 30	15.2 – 28.7	32.3 - 45.8	Max. 32.8	Yes
D1	0 - 45	18.3 – 37.8	36.9 - 56.4	Max. 35.9	Yes
D2	0 - 45	15.2 – 28.7	33.2 - 46.7	Max. 35.5	Yes
E1	45 - 90	16.8 – 36.3	37.6 – 56.8	Max. 50.0	Yes

Figure 9 shows the distribution of the number of towers used under each tower type category. The same tower type is used in different loading zones by adjusting the span length to match the critical loading. Figure 10 shows the span length between towers along the line route. It shows that in heavily loaded areas such as the high alpine areas in Labrador (zone 2) and the LRM (zone 7) the span lengths are shortened to around 150-250m.

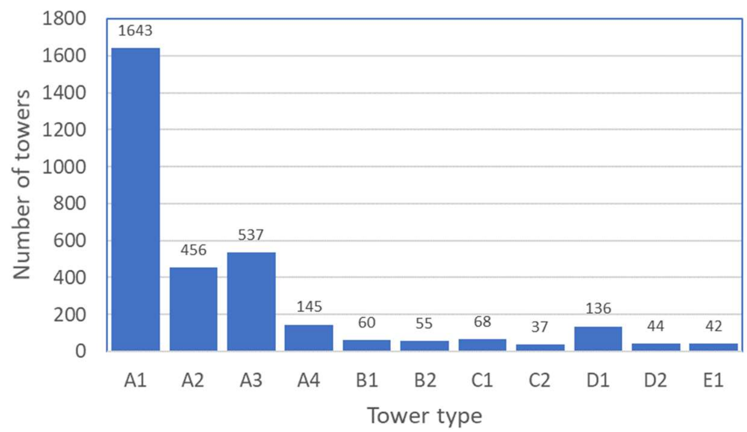

FIGURE 9 Distribution of tower type along the LITL.

Figure 10 shows a spread of the span lengths for the LITL. The spans vary mostly from 100m 500m. the heavily loaded areas such as the LRM have shorter spans, around 200m.

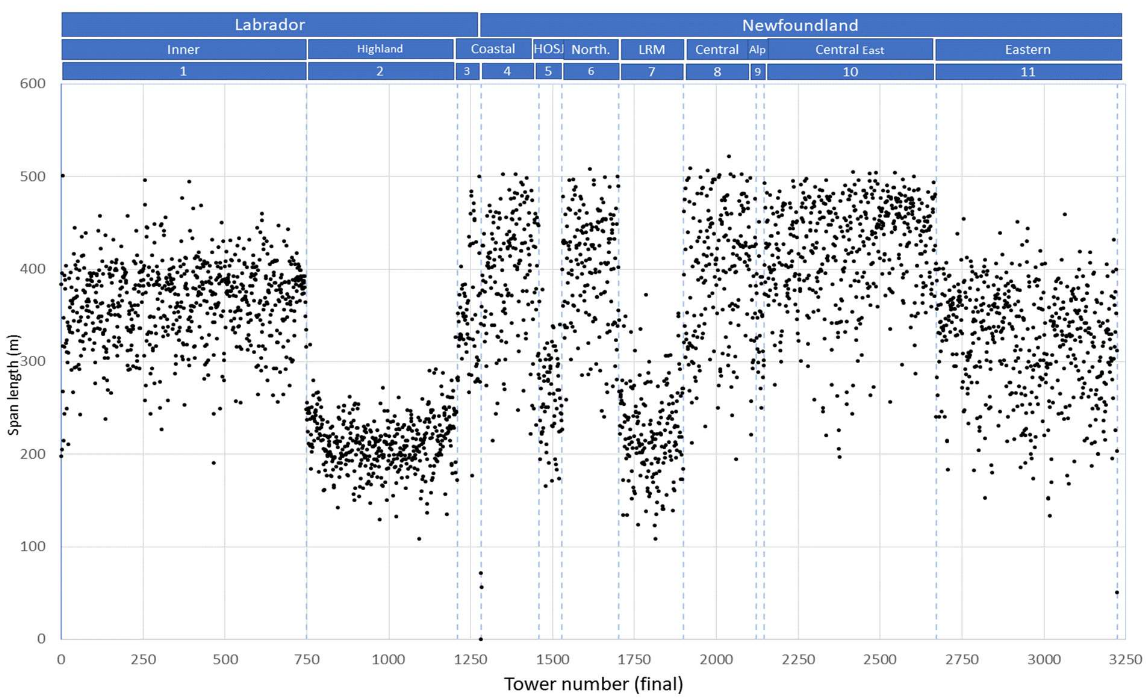

FIGURE 10 Span lengths (m) along the line route of LITL.

2.4 Foundations

The soil along the line is typically glacial till overlying rock at various depths. Table 5 shows which foundation types were used depending on soil conditions.

TABLE 5 Foundation type depending on soil condition. Ref. [4]

SOIL CONDITION	TYPE	FOUNDATION TYPE
Granular soil	Guyed tower mast	Steel grillage with single adjustable stub
	Guy anchor	Grouted in-line soil anchor
	Rigid tower leg	Steel grillage with single adjustable stub
On rock	Guyed tower mast	Steel grillage with single adjustable stub and mechanical rock anchor
	Guy anchor	Grouted in-line rock anchor
	Rigid tower leg	Steel grillage with single adjustable stub and mechanical rock anchor
Deep foundation	Guyed tower mast	H-Pile with steel cap
	Guy anchor	Grouted in-line anchor
	Rigid tower leg	H-Pile with steel cap with or without anchors
Bog foundation	Guyed tower mast	H-Pile with steel cap with or without anchors
	Guy anchor	Grouted in-line soil anchor
	Rigid tower leg	H-Pile with steel cap with or without anchors

Foundations were designed for water table depth as 1.0m and the minimum grillage foundation depth for tower types A and B was based on frost depth given in Table 6. For tower types, C, D and E, the foundation depth was taken as 3.5 m for the uplift capacity calculations.

TABLE 6 Frost Depth and Foundation Depth, ref. [5].

TRANSMISSION LINE LOCATION	CALCULATED FROST DEPTH (M)	MIN. FOUNDATION DEPTH (M)
Forteau - Muskrat Falls (Labrador 384 km)	3.0	3.25
Grand Falls- Shoal Cove (km 304 to km 695)	2.3	2.55
Sunnyside to Grand Falls (km 113 to km 304)	2.0	2.25
Soldiers Pond -Sunnyside (km 0 to km 113)	1.7	1.95

All guys, guy anchors, and foundations were designed for extreme loading for a given tower type and a tower family zone. Thus, many foundations are somewhat overdesigned since they were not calculated for actual loading at a given tower location. All guy anchors where proof tested in the field. A special test rig was used to test all the guy anchors to 100% of unfactored (working) loads, see Figure 13.

FIGURE 11 Grillage foundation installed.

FIGURE 12 Pile foundation.

FIGURE 13 Guy anchor testing.

FIGURE 14 Rock foundation, ready for concrete.

2.5 Conductors and OPGW

The LITL has ACSR pole conductors, two ACSR conductor types for the electrode lines and three types of OPGW. The details of the conductors, location and route lengths are indicated in Table 7.

TABLE 7 Conductors (pole and electrode line) and OPGW in use in LITL.

TYPE	SHORT DESCR.	CODE NAME	UTS (KN)	DIAMETER (MM)	MASS (KG/M)	LOADING ZONES	ROUTE LENGTH (KM)
Pole conductor	ACSR	1841_A1/ S1A-109/7	381.6	56.9	5.68	All loading zones	1093.6
Electrode line	ACSR	Grackle	187	33.85	2.28	Average loading zones	284.6
Electrode line	ACSR	Falcon	242	39.24	3.04	High alpine and extreme alpine loading zones	98.6
OPGW	24 fibers		142	14.5	0.79	Average loading zones	771
OPGW	24 fibers		277	20.6	1.62	High alpine and extreme alpine loading zones and Eastern loading zones.	303
OPGW	48 fibers		277	20.6	1.62	Near Soldiers Pond in NL	16

2.6 Insulators

The line has ball and socket insulators made of toughened glass with an anti-fog shed profile. The strength of insulators is shown in Table 8.

TABLE 8 Strength of insulators in use in LITL.

TYPE	SUSPENSION INSULATOR STRING (KN)	TENSION INSULATOR STRING (KN)	JUMPER INSULATOR STRING (KN)
Pole conductor	1x300 kN	2x300 kN	1x160 kN
Electrode conductor on steel towers	1x220 kN	2x220 kN	1x220 kN
Electrode conductor on wood poles	1x160 kN	2x160 kN	1x160 kN

2.7 Hardware

The strength of the hardware assemblies is indicated in Table 9. Hardware selection and design is an essential part of line design to meet the overall reliability. Experience shows that line failures are often caused by hardware failures resulting from manufacturing defects (imperfections) or aging-related degradation. A hardware failure in a tension tower can cause significant line damage, possibly triggering a cascade event. It should be noted that the design for fatigue and wear is often equally crucial for hardware as the strength requirement.

TABLE 9 Strength of critical hardware in insulator strings in use in LITL.

TYPE	INSULATOR STRING	YIELD STRENGTH (KN)	ULTIMATE STRENGTH (KN)	CRITICAL ITEM
Pole conductor	Suspension insulator string	222	302	Suspension clamp
	Tension insulator string	289	445	Turnbuckle
	Jumper insulator string	204	276	Shackle / socket-clevis
OPGW	Tension string -20.6mm	204	345	Yoke plate / shackle
	Tension string -14.5mm	204	276	Shackle/thimble/Link plate
	Suspension string -20.6mm	220	253	Yoke plate/ AGS clamp
	Suspension string -14.5mm	102	138	Suspension Clamp/Y clevis
Electrode conductor	Tension string – FALCON	222	267	Clevis ball/socket clevis
	Suspension string-FALCON	120	160	Suspension clamp
	Tension string-GRACKLE	222	267	Clevis ball/socket clevis
	Suspension string-GRACKLE	90	120	Suspension clamp
Guy Hardware	Guy Hardware assembly	510		Adjustable strain link

2.8 Influence of failure type on system performance

Different types of failures can occur in the LITL, resulting in different impacts on the overall system performance. A detailed description of the influence of each failure type on the system performance of the LITL is given in [6] for forced and planned outages. Table 10 shows a simplified version of the consequence of a failure on the power transmission ability.

TABLE 10 Influence of continuous failure on power transmission

Failure / Outage	Consequence for power transmission
OPGW	None or limited, the LITL has two backup means of telecommunication to enable continued operation (radio and telephone)
Single Electrode Conductor	Limited, power transmission reduced to half the line capacity
Electrode Line	Limited, power transmission reduced to half the line capacity
Single HVdc Pole	Medium to large
Bipole	Severe/Catastrophic

3 PROCEDURE

3.1 Methodology

This work was a collaborative effort between EFLA Consulting Engineers and Nalcor/Hydro. EFLA performed the post-processing work, interpreted the results and wrote this report while Nalcor/Hydro performed most of the structural analysis with PLS-Cadd and PLS-Tower software. Adjustments recommended by EFLA to accommodate CSA 60826-10 loadings were incorporated into the PLS-Cadd design files for the analysis. EFLA independently checked results in few PLS-Cadd and PLS-Tower models and Nalcor reviewed and commented to assumptions.

The following information was made available by Nalcor/Hydro for the study:

- Relevant Design documents
- PLS-Cadd design models and as-built line profiles
- Previous structural capacity analysis performed by SNC Lavalin, i.e., PLS-Tower models

The analysis was performed using loadings obtained from the CSA 60826-10 standard corresponding to 50, 150 and 500-years return period values as well as the "as-designed" loadings, see Table 14. The utilization with the CSA-50, 150 and 500 years were benchmarked against the "as-designed" utilization of the major line components (structures, insulators, hardware and conductors). PLS-Cadd software was used to calculate forces in all towers and cable sections based on settings from the "as-design" line using the ruling span concept (Level 1) analysis.

3.1.1 Tower analysis

Tower analysis was performed using the PLS-Tower program. Guyed towers have been modeled with all elements, but models of self-supporting tensions tower do not include all secondary redundant elements, which is an acceptable practice in tower modeling and design. Each tower was modeled with exact height.

Tower capacity is defined in [4] and seems to follow the ASCE 10-97. A review of tower models, tower detailing and tower design was not part of the scope of this study.

The strength capacity assessment is based on the PLS-Cadd and PLS-Tower models developed during LITL design. Due to the size of the LITL project and variation, the PLS-Cadd model is split into 37 different PLS-Cadd files. Following modifications were made to the PLS-Cadd and PLS-Tower files for the analysis:

- Loading was modified into CSA loading, as described in chapter 3.2. The PLS-Cadd option "IEC 60824:2017F" was selected instead of using "Wind on face" as done in the design.
- Stiffness of a few elements in seven suspension towers[6] was reduced by a factor 10 to create more realistic force distribution in the tower members.

[6] Tower Numbers: 128, 282, 286, 288, 1225, 1324 and 1687

- Improvements were made of the modeling of the earth wire peak in tower 1219 (A1) to better represent reality[7].

Redundant force[8] in secondary elements of self-supporting towers was not verified. The design of secondary elements is part of detailed design and the design is not very sensitive to moderate changes in loading.

3.1.2 Foundations analysis

The foundations were designed using the maximum design loads corresponding to maximum design span lengths and tower heights. All foundations per tower type have the same capacity irrespective of the soil type.

A foundation utilization value was calculated by comparing the actual foundation forces to the design values of the foundation design loading.

3.1.3 Conductor analysis

The allowable conductor tension limits were verified in all sections using the same settings from the "as-design" line using the ruling span concept (Level 1) analysis in the PLS-Cadd.

3.2 Strength factors for major components of the LITL

The preferential sequence of failure was defined in the LITL project as follows (ref. [7]):

1) Suspension tower types A, B
2) Angle tower Types C, D, E
3) Conductors and shield wires
4) Foundations
5) Insulators and hardware

3.2.1 Towers

The design of the LITL is based on the global strength factor in the Canadian deviations (paragraph 7.3.3) for CAN/CSA 22.3 No. 60826 as shown in Table 11.

TABLE 11 Strength factors used in the design of LITL.

COMPONENT	RESISTANCE FACTOR Φ_R	
	Intact loading cases	Failure loading cases, wire break
Suspension towers, type A and B	0.9	1.0
Tension towers, type C, D and E	0.8	0.9
Guy wire	0.7	0.9

[7] The original model of the tower earth peak used a beam element with insufficient stiffness and strength compared to reality.

[8] Secondary elements are designed for force of 2.5% of the supporting member.

Steel tower design criteria are specified in [4], the rules are mainly based on ASCE 10-97, Design of Latticed Steel Transmission Structures.

3.2.2 Foundations

Foundation design criteria are specified in [5]. The foundation load overload factor for all tower types was taken as 1.15 times the ultimate foundation loads derived from the tower design to coordinate the failure sequence[9].

When designing the structural steel grillage, a factor of 0.8 for dead-end towers and 0.9 for suspension towers were applied to the yield strength of the steel following CSA C22.3 No. 60826-10, Section 7.3.4. The overall safety factors for the tension tower and suspension tower steel grillage are 0.7 and 0.78 respectively.

3.2.3 Conductor

The CSA standard gives the following recommendation for damage and failure limits of conductors.

"*In the absence of relevant data, these values constitute acceptable design limits*."
Damage limit 75 % of the characteristic strength or rated tensile strength (typical range in 70 % to 80 %)
Failure limit Ultimate tensile stress (rupture)

Conductor, insulator and hardware design criteria are specified in [7]. In the design of LITL, the maximum allowable conductor utilization was specified in a range of 60-80% of the ultimate strength, depending on the load case. Table 12 shows the specified maximum utilization in the design of LITL.

TABLE 12 Specified maximum utilization of cables in the design of LITL in % to rated strength of the cable.

CABLE	SPECIFIED MAX. UTILIZATION (%) FOR EACH LOAD CASE				
	Wind	Rime ice	Glaze ice	Wind and ice	Max
Pole	60-70*	75	75	60-70*	75
Electrode	60	80	75	60	80
OPGW	60-70*	80	80	60-70*	80
Max	70	80	80	70	80

*70% in loading F6 and F9

It is unusual to have different tension limits of conductors depending on the type of extreme weather loading and no obvious argument supports such a difference. Therefore, in this analysis, a single tension limit is used for extreme weather conditions of all wind and ice load cases. A utilization tension limit of 80% of rated strength is used in this study for all conductors. This value is the same as proposed in the European standard EN 50341-1:2012.

[9] This safety factor is not applied to the soil data because the soil characteristics already include appropriate safety factors.

3.2.4 Insulators and hardware

Design criteria for the strength of insulators and hardware are described in [7], it specifies the following target values:

TABLE 13 Strength factors for insulators and hardware, for probabilistic loading.

TYPE OF INSULATOR STRING	INSULATORS	HARDWARE
Suspension string	0.5	• Shall withstand 100% of insulator(s) strength rating • Shall withstand 80% of insulator(s) strength rating without permanent deformation
Tension string	0.5	• Shall withstand 1.15 X the combined RTS of all sub-conductors • Shall withstand 1.0 X the combined RTS of all sub-conductors without any permanent deformation

In most standards, the safety factor for the tension hardware is equal or greater than that for the suspension hardware. In the LITL design requirements, the requirement is reversed, i.e. the suspension hardware has a safety factor of 2 and the tension hardware safety factor is 1.44 when the conductor is utilized at 80% of RTS. The safety factor of 2 is considered as rather high when compared with other design standards while 1.44 may be on the lower end for the tension hardware.

3.3 Criteria for wind and ice loading according to CAN/CSA C22.3 NO.60826-10

This section compares the design criteria for the LITL as well as the as designed capability against the applied meteorological loadings specified in CAN/CSA 60826-10. Differences in the loading criteria are provided as well as an evaluation of the loading impact on the towers, conductors, hardware, and insulators. The criteria used for the evaluation are:

- Glaze ice precipitation
- Wind Loading
- Combined Wind and Ice loading

Rime ice will be treated in a separate report with updated climate loads.

This study considers only load cases that influence the reliability of the LITL, i.e., load cases related to wind, ice, and a combination of wind plus ice. All load cases related to security level[10] and safety level[10] are ignored.

3.3.1 Load cases for climatic loading

Some simplifications are made in this study and the number of load cases has, therefore, been decreased from the DESIGN of LITL.

Following assumptions/simplifications are made in the study:

- Assumptions from the design of LITL are followed unless they conflicted with CSA Standard.
- Wind direction is assumed transversal, 45°, or longitudinal to spans.
- Ice load on tower members is assumed the same as radial ice on a conductor.
- Load cases contain only uniform ice formation.

[10] Refer to definitions

- Load cases not relevant to reliability analysis were removed from the analysis.
- The unbalance ice load case was removed from the analysis as it was generally not the controlling load case[11,12].
- Due to the size of the LITL the designers needed to split the PLS-Cadd model into separate models, 37 models were used. The towers on the end of each model is studied in less detail than other towers in this document[13].

The specified load cases should represent the critical load cases for suspension towers[14] very well and provide a good overview of the actual as-built designed capacity. Overall, the capacity of the suspension towers is of primary concern since they are the ones first to fail when the line is overloaded, according to chapter 3.2. Tension towers are designed with higher safety factors and usually designed for more conservative load cases than suspension towers. Consequently, they should be more reliable than the suspension towers.

3.3.2 Wind and ice loading used in the design of LITL

The following sources of data were used to establish the design load conditions for the LITL:

- Reference wind and ice load as provided in the CSA standard;
- A study on glaze ice undertaken by Kathleen Jones of the Cold Regions Research and Engineering Laboratory [8];
- Studies made by Landsvirkjun Power which evaluated rime (or in- cloud) ice loadings, which are a design consideration along the LITL's route [9], [10];
- Hydro's applicable nearly 50-year operating history along the transmission line route.
- Measurements in test spans at LRM that measure rime icing
- Studies completed by Meteorology Research Inc., Teshmont, and RSW.

[11] Load case used in study are usually the governing load cases related to reliability loading. Thorough detailed design should include more global wind directions and combination of unbalanced ice formation between sections in order to cover possible special cases.

[12] Tension towers in LITL were designed for "extreme unbalanced ice" with full ice load on one side and no conductor on the other side, for one conductor at a time. This load case is a security load case and not included in this study.

[13] A separate PLS-Cadd file with overlapping sections is needed to analyze the towers on each end of the model with correct loading.

[14] Defining all load cases for tension towers is more complicated than for suspension towers since wind direction must be varied to obtain the worst case loading on the tower. Ice loading between sections for large angles must also be varied as this could result in critical loading.

- Climatological Monitoring Program from 1973-1987 concerning transport power to Newfoundland from the proposed GULL ISLAND PROJECT in Labrador. Measurements and monitoring program.

Nalcor quantified the loading based on available information and made different loading zones along the line route. Table 14 shows the loading zones, the specified load values and other relevant information.

TABLE 14 Loading conditions for each loading zone as used in the structural design of LITL.

Zones with rime icing are presented with gray color.

ZONE		DESCRIPTION	WIND*	ICE**		Wind & Ice	
			(km/h)	Type	Radial (mm)	Wind (km/h)	Radial ice (mm)
Labrador	1	Av. Zone 1	105	G	50	60	25
	2a	Labrad. High Alp.	135	R	115	95	60
	2b	Labrad. Extr. Alp.	135	R	135	95	70
	2c	Labrad. High Alp.	135	R	115	95	60
	3a	Average Zone 2	120	G	50	60	25
	3b	Average Zone 2	120	G	50	60	25
Newfoundland	4b	Average Zone 2	120	G	50	60	25
	4a	Average Zone 2	120	G	50	60	25
	5	HOSJ High	150	R	115	105	60
	6	Average Zone 2	120	G	50	60	25
	7a	LRM High Alpine	180	R	115	125	60
	7b	LRM Extr. Alpine	180	R	135	125	70
	7c	LRM High Alpine	180	R	115	125	60
	8a	Average Zone 2	120	G	50	60	25
	8b	Average Zone 1	105	G	50	60	25
	9	Alpine	130	G	75	60	45
	10	Average Zone 1	105	G	50	60	25
	11a	Eastern Zone	130	G	75	60	45
	11b	Eastern Zone	130	G	75	60	45

*10 min. Average Wind Speed at 10 m Height Above Ground

** Icing type is either “R”=rime or “G”=glaze (i.e., freezing rain or freezing drizzle)

Further explanation of design loading assumptions:

- One type of ice was considered in each loading zone based on the dominant icing type. Rime ice was specified in zones 2a-2c, 5 and, 7a-7c. Glaze ice was specified in other zones. Rime icing is the critical icing loading case for 158 km (15%) of the line and the glaze ice for 922 km (85%).

- Terrain roughness category for the wind was assessed as category B[15] for areas with rime ice (i.e., zones 2a, 2b, 2c, 5, 7a, 7b and 7c) but category C[16] for all other areas.
- Wind speeds were increased in zones 2a-2c, 5, 7a-7c and 9 partly to account for local topographical effects. The wind speeds were increased by a factor of 1.64 in zone 7a, 7b and 7c compared to values specified in CSA/CAN. Topography effects were not considered in other loading zones.

The reference value of air density (ρ) in CSA 60826-10 is equal to 1.225 kg/m^3 at a temperature of 15 °C and an atmospheric pressure of 101.3 kPa at sea level. Air density correction factor (τ) is used to correct air density for different temperatures and atmospheric pressure (altitude). The CSA Canadian deviations specify in paragraph 6.2.5 an air density factor of 1.04 for wind conditions without ice and 1.1 for combined ice and wind. These factors may also be used for mountainous regions because the reduced temperature compensates for the altitude.

LITL was designed using slightly different values of the air correction factor. τ was assessed according to Table 5 in CSA and range of 1,09-1,14[17] for the load case maximum wind and range of 1,03-1,08[18] for the load combination of wind and ice. In most zones, it leads to 10% higher wind pressure in case of wind without ice and 2% lower wind pressure in case of wind combined with ice.

All icing was assumed as radial ice on conductors. Icing accumulation on towers was included in the design. Density was assumed as 900kg/m^3 for glaze ice and 500 kg/m^3 for rime ice.

FIGURE 15 Glaze ice from the conductor, 1984 storm. Photo from ref. [11].

FIGURE 16 Rime ice at LRM in Dec. 1976.

[15] Category B is defined as "*Open country with very few obstacles, for example airports or cultivated fields with few trees or buildings*".

[16] Category C is defined as "*Terrain with numerous small obstacles of low height (hedges, trees and buildings)*".

[17] τ = 1,14 for wind in most zones, see in Table 17.

[18] τ = 1,08 for wind and ice in most zones. τ = 1,06 in zone 5 and 1.03 for zones 7a, 7b and 7c.

3.3.3 Wind loading according to CSA

Four main factors influence the basic wind pressure on structure:

- Reference wind speed (10-minute average) at terrain category B
- Selection of terrain category (A, B, C or D)
- Evaluation of local wind condition
- Air density correction factor for temperature associated with extreme wind speed

The CSA standard gives a 10-minute average reference wind speed for 50-years return period in terrain category B with contour lines, see Figure 17. The CSA standard also specifies conversion factors to modify the return period into 150 and 500-years return periods, see Table 15.

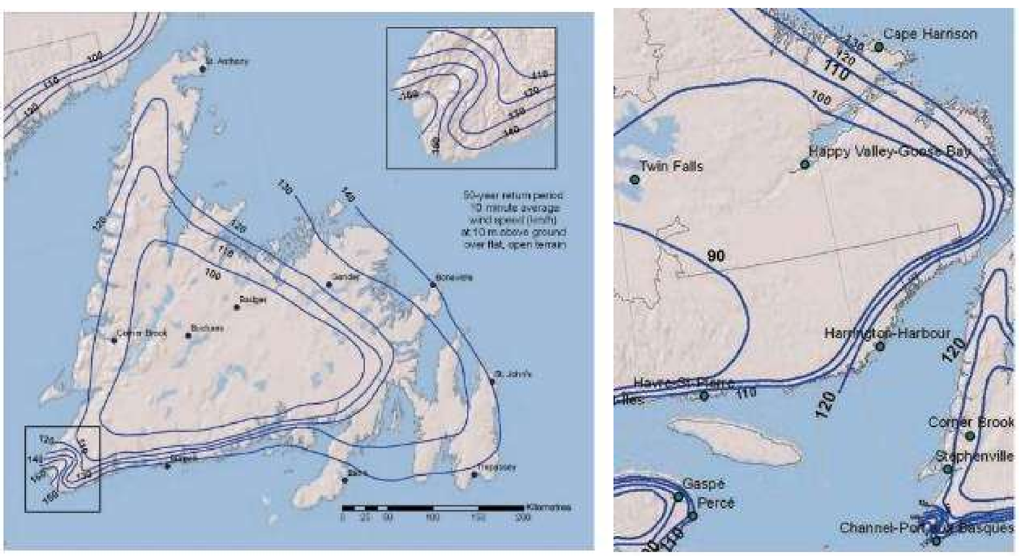

FIGURE 17 Reference 50-year return period wind speed (km/h) for Newfoundland and Labrador, Figures CA.1 and CA.3 in the CSA standard.

TABLE 15 Scaling factors γ_T to modify the 50-year return period weather variable to other return periods. Table CA.2 in CAN/CSA C22.3 No. 60826-10.

RETURN PERIOD (YEARS)	WEATHER VARIABLE	
	Wind speed γ_{Tw}	Ice thickness γ_{Ti}
50	1.00	1.00
150	1.10	1.20
500	1.20	1.42

Terrain category influences both average wind speed (increases with less roughness) and gust (increases with higher roughness). Table 16 shows guidelines on selection of terrain category given in CSA as well as the relative wind load that the terrain category has on conductor at different heights.

TABLE 16 Terrain category for wind.

TERRAIN CATEGORY	ROUGHNESS CHARACTERISTIC	RELATIVE INFLUENCE ON WIND LOADING, COMPARED TO CATEGORY B		
		10 m height	20 m height	30 m height
A	Large stretch of water upwind, flat coastal areas	1.08	1.09	1.06
B	Open country with very few obstacles, for example, airports or cultivated fields with few trees or buildings	1.00	1.00	1.00
C	Terrain with numerous small obstacles of low height (hedges, trees and buildings)	0.80	0.83	0.83
D	Suburban areas or terrain with many tall trees	0.55	0.58	0.58
CSA on terrain category in Canada (paragraph 6.2.2) *"Terrain type B is representative of the majority of lines and should lead to acceptable results in all areas except in flat coastal areas, where a terrain type A should be used."*				

Large portion of the LITL is in a track that required tree clearing. Thus, based on the description in Table 16 it can be argued that large portion of LITL should be in terrain category C. It was not part of this study to assess the suitability of the terrain category selection or local wind effects used in the design assumption for the LITL. The study uses the terrain categories as selected by the designers of LITL and used in DESIGN loading.

Regarding local wind effects, the CSA standard has limited guidelines compared to some other standards. It does state:

> *Furthermore, the effects of acceleration due to funneling between hills or due to sloping grounds are not covered and may require specific studies to assess such influences.*

When assessing the CSA wind speed, reference wind values from CSA maps as shown in Figure 17 were used. Table 17 presents a comparison of the wind speed for each loading zone and values for the reference design wind speed (V_R), air density correction factor (τ) and terrain type used to calculate the wind pressures. Values, according to CSA, were evaluated based on Figures CA.1 and CA.3 in the CSA 60826-10 standard. The wind velocity for 150 years return period is 10% higher than the 50 years value and the 500 years value is 20% higher than the 50 years value, according to scaling factors presented in Table 15.

Figure 18 presents the ratio of CSA wind pressures for 50, 150 and 500-year return periods to the design wind pressure for each zone. A ratio of less than 1.0 indicates the design wind pressure is higher than the CSA wind pressure. The pressure used for design is always larger than the CSA-50-year return period. While some areas have CSA-150 pressure higher than the design value; the towers may not be utilized to maximum capacity and hence are strong enough to withstand the CSA-150-year wind pressures. Refer to chapter 4 for the results of the tower strength capacity.

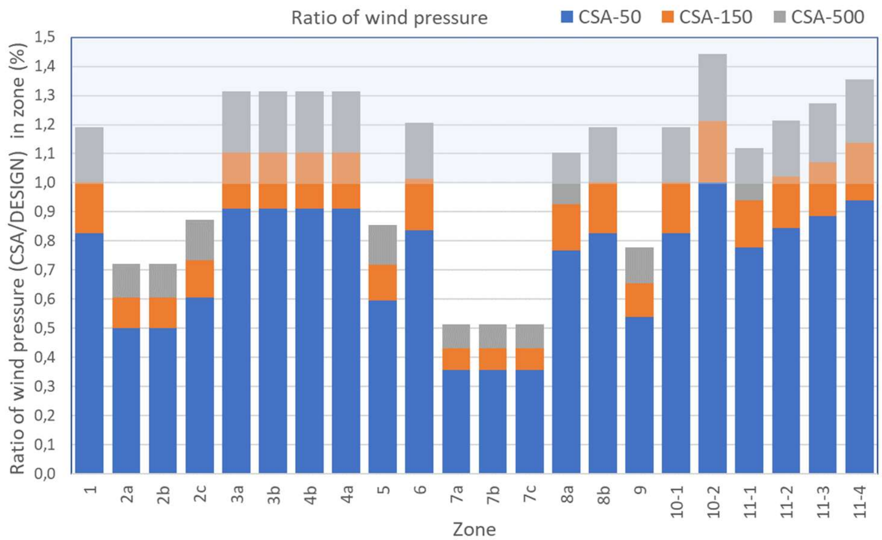

FIGURE 18 Ratio of wind pressure according to CSA (50, 150 or 500) against DESIGN wind pressure.

TABLE 17 Wind loading. Reference wind speed used in the study. DESIGN loading and CSA loading.

Zone		Length	Task		Height range a.s.l.			Area	DESIGN			CSA, ref. wind V_R		
		km	Final tow. Numb.	Final tow. Numb.	Min. (m)	Aver. (m)	Max. (m)		Ref. Wind V_R (km/h)	Air corr. factor τ	Terrain categ.	CSA-50 (km/h)	CSA-150 (km/h)	CSA-500 (km/h)
Labrador	1	272	1	750	18	389	551	Inner Labrador	105,0	1,14	C	100,0	110,0	120,0
	2a	12	750	802	337	384	423	Labrad. High Alp.	135,0	1,14	B	100,0	110,0	120,0
	2b	63	802	1110	319	376	432	Labrad. Extr. Alp.	135,0	1,14	B	100,0	110,0	120,0
	2c	22	1110	1209	224	282	346	Labrad. High Alp.	135,0	1,14	B	110,0	121,0	132,0
	3a	12	1209	1246	209	257	300	Labrador Coast	120,0	1,14	C	120,0	132,0	144,0
	3b	13	1246	Gantry	15	122	224	Labrador Coast	120,0	1,14	C	120,0	132,0	144,0
Newfoundland	4b	13	1283	1316	13	27	40	Northern Pen. Coast	120,0	1,14	C	120,0	132,0	144,0
	4a	56	1316	1457	39	121	279	Northern Pen. Coast	120,0	1,14	C	120,0	132,0	144,0
	5	19	1457	1529	250	373	499	HOSJ High	150,0	1,12	B	120,0	132,0	144,0
	6	70	1529	1703	48	129	373	Northern Peninsula	120,0	1,14	C	115,0	126,5	138,0
	7a	23	1703	1806	389	476	533	LRM High Alpine	180,0	1,09	B	110,0	121,0	132,0
	7b	8	1806	1846	526	559	606	LRM Extr. Alpine	180,0	1,09	B	110,0	121,0	132,0
	7c	13	1846	1900	371	481	587	LRM High Alpine	180,0	1,09	B	110,0	121,0	132,0
	8a	13	1900	1935	402	487	539	Central-West NF	120,0	1,14	C	110,0	121,0	132,0
	8b	75	1935	2122	90	260	483	Central-West NF	105,0	1,14	C	100,0	110,0	120,0
	9	8	2122	2145	245	374	494	Birchy Narrows	130,0	1,14	C	100,0	110,0	120,0
	10-1	142	2145	2490	43	183	353	Central-East NF	105,0	1,14	C	100,0	110,0	120,0
	10-2	79	2490	2671	35	190	302	East. NF: Gander Lake to Port Blandford	105,0	1,14	C	110,0	121,0	132,0
	11-1	33	2671	2769	40	144	263	East. NF : Port Blandford to Sunnyside	130,0	1,14	C	120,0	132,0	144,0
	11-2	89	2770	3048	15	103	206	East. NF : Sunnyside to Whitbourne	130,0	1,14	C	125,0	137,5	150,0
	11-3	37	3048	3165	45	110	247	East. NF: Whitbourne to Rod and Gun Club	130,0	1,14	C	128,0	140,8	153,6
	11-4	18	3166	3223	161	214	278	East. NF: Rod and Gun Club to Soldier's Pond	130,0	1,14	C	132,0	145,2	158,4

From table 17 it can be observed that:

- Reference wind speed in zones 2a, 2b, 2c, 5, 7a, 7b, 7c and 9 is considerably higher in "as-designed" than the CSA wind speed. This is due to the assessment of local wind in the DESIGN loading while the effects are not included in the CSA loading. These zones are around 15.4% of the overall line route.
- The terrain category in the design is selected as type B in areas expecting rime cloud icing but otherwise, type C.

3.3.4 Glaze ice according to CSA

Glaze ice on overhead transmission lines in Newfoundland has historically been one of the most significant threats regarding operational reliability. Glaze ice accumulates in freezing rainstorms and typically occurs when warm air hovers over a region, while the ambient temperature is near 0°C, and the ground temperature is sub-freezing.

The CSA standard specifies reference 50-years ice thickness (mm) at 10 m above ground over flat, open terrain from freezing precipitation, see Figure 19. In the CSA standard, the structure loads are obtained by multiplying the reference load by a spatial factor of 1.3 and a height factor of 1.15, as per Clause 6.3.4.1 of the CSA. The spatial factor is to cover local influence and the height factor accounts for transmission conductors often being over 30m.

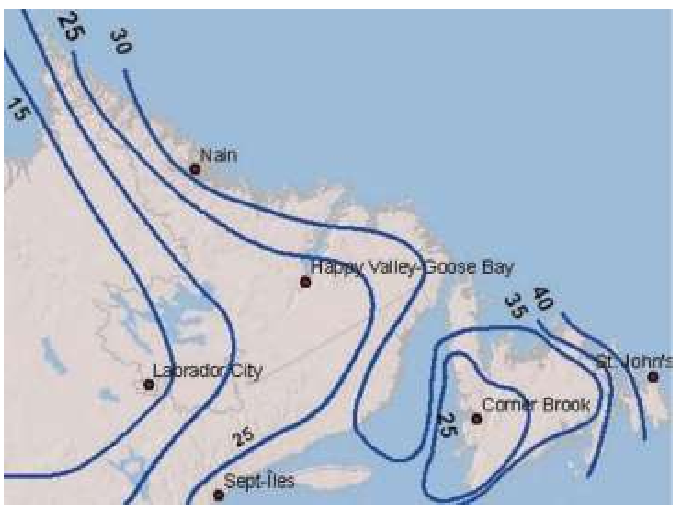

FIGURE 19 Reference 50-year return period of glaze ice thickness(mm) from freezing precipitation for Newfoundland and Labrador, figures CA.10 in the CSA standard. The structural load is obtained by adding spatial factor and height factor to these values.

Table 18 presents a comparison of the design value and CSA values for glaze icing per loading zone. Design icing was either taken as glaze ice ("G") or rime ice ("R"). The table shows reference values of the CSA loading as obtained from maps (see Figure 19) and final CSA values for 50, 150 and 500 years loading. The CSA standard does not provide recommended design values for rime ice; hence this was omitted from Table 18.

TABLE 18 Glaze icing used in "as-designed" structure and comparison to CSA 2010.

Zone		Length	Task		Height range a.s.l.			Area	DESIGN		CSA - Glaze ice (radial ice)			
		km	Final tow. Numb.	Final tow. Numb.	Min. (m)	Aver. (m)	Max. (m)		Type	Radial (mm)	Ref. value (mm)	CSA-50 (mm)	CSA-150 (mm)	CSA-500 (mm)
Labrador	1	272	1	750	18	389	551	Inner Labrador	G	50	25	37,4	44,9	53,1
	2a	12	750	802	337	384	423	Labrad. High Alp.	R		30	44,9	53,8	63,7
	2b	63	802	1110	319	376	432	Labrad. Extr. Alp.	R		30	44,9	53,8	63,7
	2c	22	1110	1209	224	282	346	Labrad. High Alp.	R		30	44,9	53,8	63,7
	3a	12	1209	1246	209	257	300	Labrador Coast	G	50	30	44,9	53,8	63,7
	3b	13	1246	Gantry	15	122	224	Labrador Coast	G	50	30	44,9	53,8	63,7
Newfoundland	4b	13	1283	1316	13	27	40	Northern Pen. Coast	G	50	30	44,9	53,8	63,7
	4a	56	1316	1457	39	121	279	Northern Pen. Coast	G	50	30	44,9	53,8	63,7
	5	19	1457	1529	250	373	499	HOSJ High	R		30	44,9	53,8	63,7
	6	70	1529	1703	48	129	373	Northern Peninsula	G	50	30	44,9	53,8	63,7
	7a	23	1703	1806	389	476	533	LRM High Alpine	R		25	37,4	44,9	53,1
	7b	8	1806	1846	526	559	606	LRM Extr. Alpine	R		25	37,4	44,9	53,1
	7c	13	1846	1900	371	481	587	LRM High Alpine	R		25	37,4	44,9	53,1
	8a	13	1900	1935	402	487	539	Central-West NF	G	50	25	37,4	44,9	53,1
	8b	75	1935	2122	90	260	483	Central-West NF	G	50	25	37,4	44,9	53,1
	9	8	2122	2145	245	374	494	Birchy Narrows	G	75	25	37,4	44,9	53,1
	10-1	142	2145	2490	43	183	353	Central-East NF	G	50	27,5	41,1	49,3	58,4
	10-2	79	2490	2671	35	190	302	East. NF: Gander Lake to Port Blandford	G	50	28	41,9	50,2	59,4
	11-1	33	2671	2769	40	144	263	East. NF : Port Blandford to Sunnyside	G	75	32,5	48,6	58,3	69,0
	11-2	89	2770	3048	15	103	206	East. NF : Sunnyside to Whitbourne	G	75	37,5	56,1	67,3	79,6
	11-3	37	3048	3165	45	110	247	East. NF: Whitbourne to Rod and Gun Club	G	75	40	59,8	71,8	84,9
	11-4	18	3166	3223	161	214	278	East. NF: Rod and Gun Club to Soldier's Pond	G	75	40	59,8	71,8	84,9

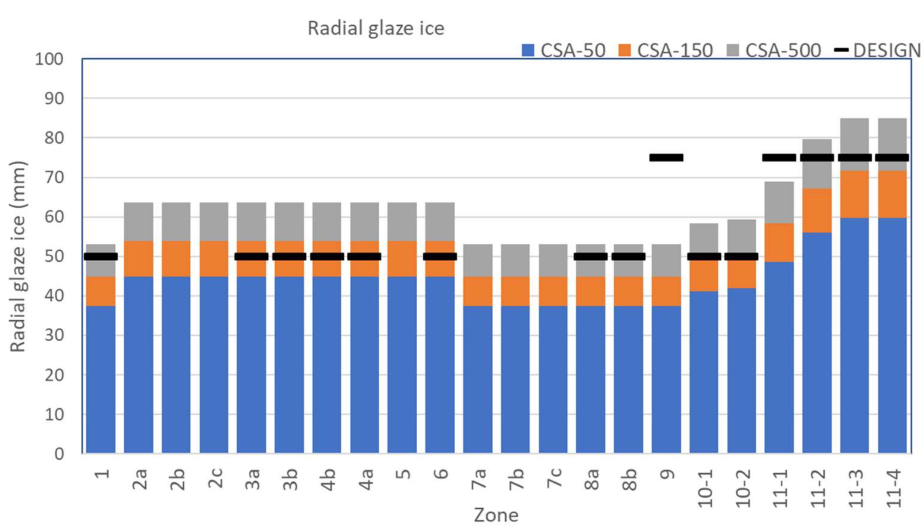

FIGURE 20 Radial glaze ice loading, CSA-50, CSA-150, CSA-500 and DESIGN.

From Table 18 and Figure 20, it can be observed that:

- Design glaze ice loading is always higher than the CSA-50 years glaze ice loading by at least 5mm and, on average 12.9 mm for all zones and 10.1 mm if average weighted by length is used.

- Design glaze ice loading is in many zones above the CSA-150 loading. In total, there are 70 km (zones 3a, 3b, 4b, 4a and 6) where glaze ice is 3.8 mm higher in the CSA-150 loading than the "as-designed" line loading.
- The CSA-500 years loading is often higher than the "as-designed" loading. The largest difference is 13.7 mm radial ice. Zone 9 and 11-1 design values are higher than the CSA-500 value.
- Glaze ice loading is not presented in DESIGN loading for zones: 2a, 2b, 2c, 5, 7a, 7b and 7c since rime ice is the dominant ice loading in those zones.

3.3.5 Combined wind and ice loading

The CSA Standard specifies two loading combinations for wind and ice in case of freezing rain. Here they are identified as "*Wind and ice*" when the wind is the primary loading and "*Ice and wind*" when ice is the primary loading. Table 19 shows the CSA proposed values of wind speed and ice load when statistical analysis cannot be completed on reliable data from icing episodes.

TABLE 19 Definition of combined loading with wind and ice in the CSA Standard.

	Wind and Ice	Ice and wind
Ice load	0.40 g_R	g_R
Wind speed	(0.60 to 0.85) · V_R	(0.4 to 0.5) · V_R
Description	Low probability wind during icing (return period T) associated with the average of the maximum yearly icing	Low ice probability (return period T) associated with the average of yearly maximum winds during icing presence

g_R is reference design ice load (N/m) for the specified return period (T= 50, 150 or 500 years)

V_R is reference wind speed for the specified return period (T= 50, 150 or 500 years)

In the design of the LITL, the wind speed in the load case "Wind and Ice" was taken as 60 km/hour in combination with glaze ice. It leads to wind speed in a range of 0.46 to 0.57 V_R for the load case "Wind and Ice" in the case of glaze ice, see Table 14. The factor of 0.7 is used for rime ice.

Following assumptions are made in the study:

- In this study, a wind speed of 0,6 · V_R is used for the load case "Wind and Ice" in case of glaze ice.
- All design in the LITL was based on using radial ice in the PLS-Cadd models. It was not possible to define the ice load in "Wind and Ice" as 0.40 g_R without considerable modification. Therefore, a simple approach was made with approximating the loading as 0.58 of the radial ice loading. It overestimates the icing in case of pole conductor and electrode conductor but slight underestimation in case of small OPGW with high ice load.
- In this study, a wind speed of 0,4 · V_R is used for the load case "Ice and Wind" in case of glaze ice.
- The drag coefficient of conductor covered with glaze ice is assumed = 1.0, which is recommended in Table 8 of the CSA 60826-10 standard.

3.3.6 Ice Loading on tower body

Glaze ice will accumulate on the tower members during icing condition. The CSA states that ice accretion on structures should be considered (paragraph 6.3.2) and that it can reach or exceed the weight of the structure itself in case of radial ice thickness greater than 30-40 mm. An alternative approximation of ice load on tower can be derived as a ratio of tower weight (paragraph A.5.8.3).

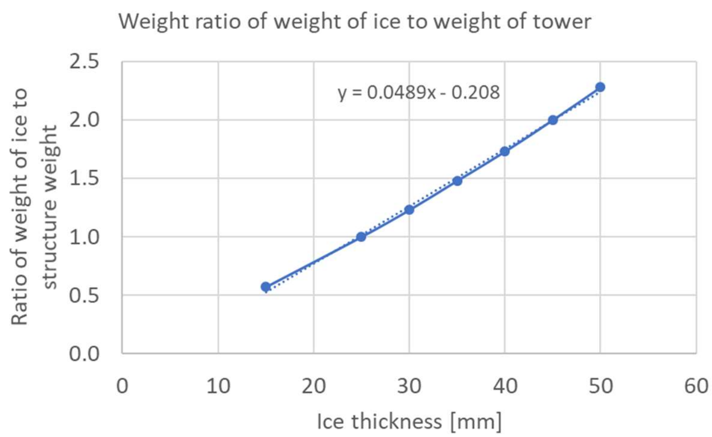

FIGURE 21 CSA alternative approximation of ice weight on tower based on tower weight and ice thickness.

In design of the LITL the assumption was made that ice on tower members was a radial cover on each profile using the same radial ice thickness as specified on the conductors. This approach is conservative, and it ignores the shielding effects of nearby profiles and no-rotational influence of profiles[19].

This study uses the same assumption of ice load on towers as in the design of the LITL. Total ice weight on towers was checked in few critically loaded towers and generally found to be very conservative[20]. For few critical suspension towers the influence of icing on towers is presented using both methods, see Table 20.

[19] Radial ice builds-up on conductors because conductors rotate due to torsional moment when icing accumulation occurs. Torsionally stiff conductors accrete less ice in extreme cases.

[20] In tower 3212 (zone 11-4) the ice weight in the load case "Max. Ice" with full radial ice in CSA-150 is 44 ton, which is a weight ratio of ice to tower of 5.3. The conductor radial ice is 71.8 mm, thus the ratio should be 3.3 when using Figure 21.

4 RESULTS OF ANALYSIS OF LITL WITH CSA LOADING – WIND AND GLAZE ICE

4.1 General

Results of the capacity assessment for DESIGN and CSA loading are presented in this chapter. The following load cases impacting the line reliability were used in the analysis:

- Max. Wind
- Glaze ice
- Wind with ice
- Ice with wind

As described in chapter 3.3, these load cases impact the line reliability requirements. The assumptions and methodology used in the analysis are stated in chapter 3. The same load cases were utilized to evaluate the capacity of the towers, foundations, conductors, insulators and hardware. The results for the DESIGN loading include analysis of the rime ice loads (zones 2,5 &7) however the CSA load results exclude rime ice. The CSA standard does not provide recommended values for rime ice loads hence only glaze ice was evaluated and presented in the CSA results. A separate study will be conducted on the rime ice and the utilization values for the affected zones will be updated.

4.2 Suspension towers

For all the wind load cases, wind is applied transverse, 45 degrees and longitudinal to the line. The ice is applied evenly to all sections during the analysis.

Figure 22 shows the highest utilization in all suspension towers in the LITL in all load cases mentioned above in DESIGN loading. Most towers are below 80% utilization with two towers are above 90% utilization and highest utilization is 99.9%. The figure indicates that most towers have reserve capacity.

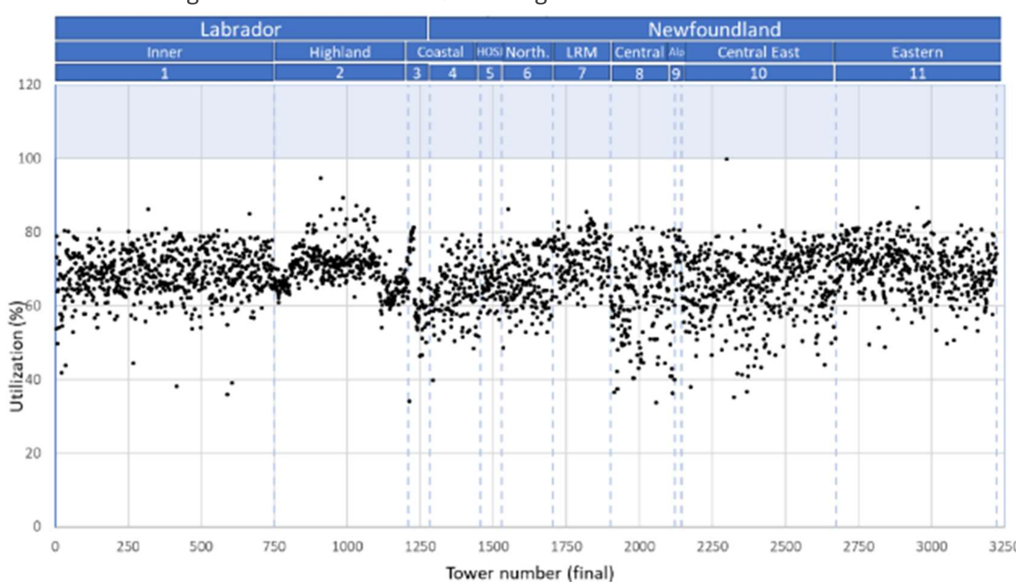

FIGURE 22 Utilization in all suspension towers for DESIGN loading.

Figure 23 presents the results of the DESIGN and CSA-50, CSA-150 and CSA-500 climatic loading analysis and reports the "maximum utilization" for a single critical suspension tower per zone. The DESIGN loading results in the critical tower utilization averaging 80% in all zones not designed for rime ice. The critically loaded tower in zone 10-1 has utilization close to 100% under max ice loading.

For the CSA-50 loading, all use factors are below that of the DESIGN condition. Two towers are above 90% utilization and the highest utilization is 99.9% (Tower 2298) in zone 10-1. Tower 2298 has high capacity utilization in one diagonal member in the earth wire peak.

The critical load case for the CSA-150 loading is "*Wind + Ice*". Eight towers have utilization up to 104% in zone 3a and 11-4. With the CSA-500 loading, eleven zones have tower utilisation greater than 100%. Figure 24 presents the highest utilization of the critical tower per load case. Figure 25 shows the highest utilization in all suspension towers in the LITL in all load cases for CSA-150 loading. Table 20 presents the 20 most critical suspension towers for the different load criteria.

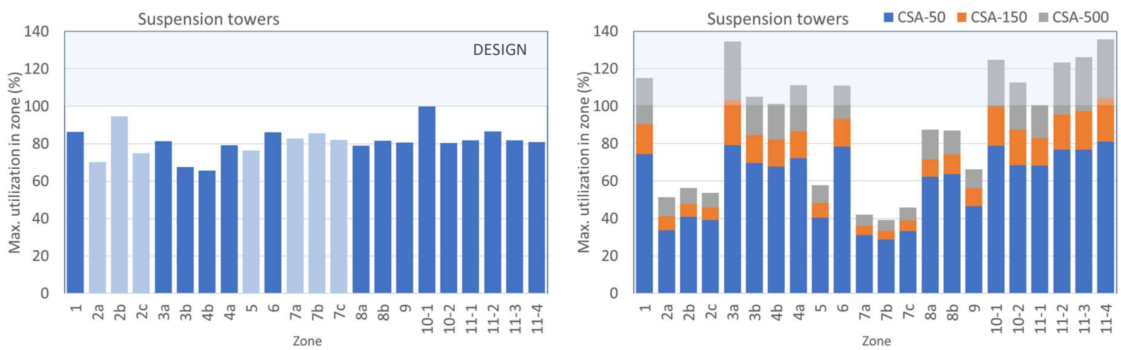

FIGURE 23 Highest utilization in all suspension towers by zone. Results for DESIGN loading[21] is to the left and CSA loading to the right. Includes all load cases described in chapter 3.3.

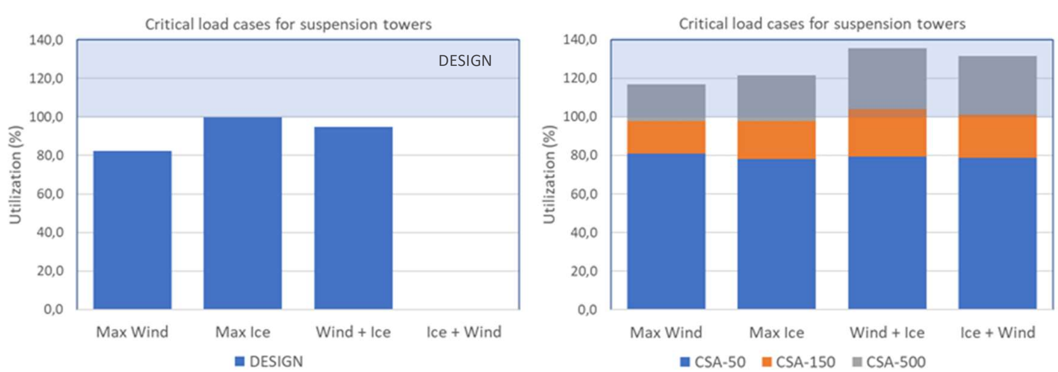

FIGURE 24 Highest utilization in suspension tower for each load case.

[21] The DESIGN loads include rime ice for zones 2, 5 and 7. The CSA loading does not include rime ice in this study.

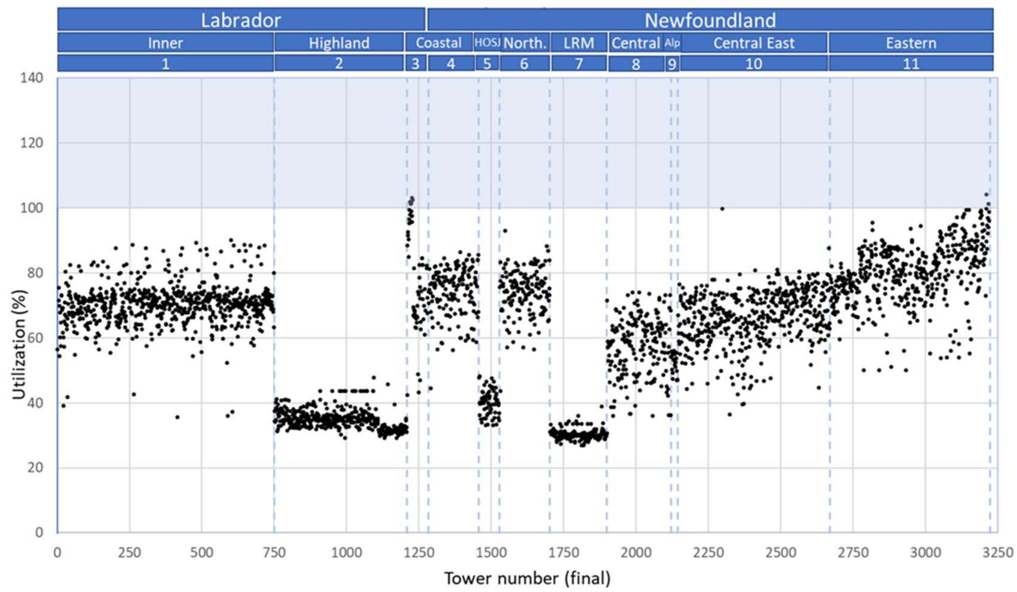

FIGURE 25 CSA-150 loading, highest utilization in all suspension towers. Includes all load cases described in chapter 3.2.

TABLE 20. Twenty most critical suspension towers for each loading.

DESIGN				CSA-50				CSA-150				CSA-500			
Tow.	Type	Zone	Max	Tow.	Type	Zone	Max	Tow.	Type	Zone	Max *	Tow.	Type	Zone	Max
2298	A1	10-1	99.9	3212	A3	11-4	81.1	3212	A3	11-4	104.1 (100.3)	3212	A3	11-4	135.6
909	B1	2b	94.7	1227	A1	3a	79.0	1227	A1	3a	103.2 (100.8)	1227	A1	3a	134.6
984	B1	2b	89.3	2298	A1	10-1	78.9	1228	A1	3a	102.5 (100.1)	1219	A1	3a	133.7
1032	B1	2b	87.1	3142	A3	11-4	78.8	1219	A1	3a	101.8 (99.4)	1222	A1	3a	133.7
2950	A3	11-2	86.7	1228	A1	3a	78.4	1224	A1	3a	101.5 (98.8)	1228	A1	3a	133.6
1070	B1	2b	86.3	1549	A1	6	78.4	1222	A1	3a	101.4 (99.0)	1224	A1	3a	132.1
951	B1	2b	86.3	3191	A3	11-4	78.3	1221	A1	3a	101.2 (98.8)	1221	A1	3a	132.1
319	A1	1	86.3	1222	A1	3a	78.0	3219	A3	11-4	101.2 (98.8)	3219	A3	11-4	131.6
976	B1	2b	86.2	3194	A3	11-4	77.9	2298	A1	10-1	99.9	3211	A3	11-4	130.2
1549	A1	6	86.2	3193	A3	11-4	77.8	3211	A3	11-4	99.8	1218	A1	3a	129.6
1067	B1	2b	85.6	3219	A3	11-4	77.8	3142	A3	11-4	99.5	3142	A3	11-4	129.5
1819	A4	7b	85.5	1219	A1	3a	77.7	1218	A1	3a	99.5	1225	A1	3a	129.0
665	A1	1	85.0	3150	A3	11-4	77.7	3150	A3	11-4	99.3	3150	A3	11-4	128.9
1048	B1	2b	84.7	3211	A3	11-4	77.6	3193	A3	11-4	99.2	3193	A3	11-4	128.8
908	A2	2b	84.4	1221	A1	3a	77.5	1223	A1	3a	99.1	1223	A1	3a	128.6
1091	B1	2b	84.0	3220	A3	11-4	77.5	3191	A3	11-4	98.8	3220	A3	11-4	128.6
1832	A4	7b	83.7	1224	A1	3a	77.2	3220	A3	11-4	98.8	3191	A3	11-4	128.4
1058	B1	2b	83.5	3192	A3	11-4	77.2	3192	A3	11-4	98.7	3192	A3	11-4	128.4
997	B1	2b	83.5	3135	A3	11-4	77.1	3134	A3	11-4	98.1	1220	A1	3a	127.4
1021	B1	2b	83.3	3216	A3	11-4	77.0	1220	A1	3a	97.9	3134	A3	11-4	127.3

* Values within bracket are calculated with icing on tower members according to the CSA approach described in paragraph 3.3.6. They are more accurate results and are used hereafter.

4.3 Tension towers

Figure 26 presents a summary of the results on the analysis of 320 tension towers grouped by zone[22]. The DESIGN and CSA loading results are presented for the critical tower per zone. Table 21 shows the 20 most critically loaded tension towers.

The results show that the utilization for the tension towers for the DESIGN and loads up to CSA-150 loading is below 100%. When the CSA-500 loading is applied, six tension towers in zone 11 exceed 100% utilization.

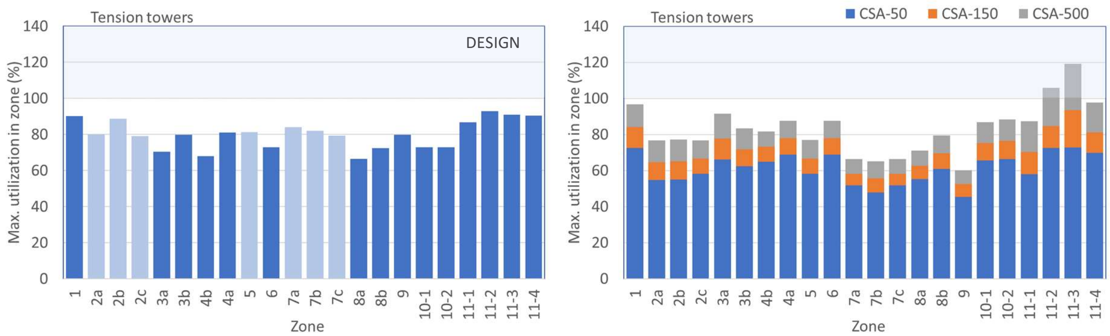

FIGURE 26 Highest utilization in tension towers[21] in the load cases "Max. Ice", "Max. wind" and "Wind + ice" and "Ice + wind". Without towers on the model ends. Results for DESIGN loading is to the left and CSA loading to the right.

TABLE 21. Twenty most critically loaded tension towers for each loading. Without the end towers in each PLS model

DESIGN				CSA-50				CSA-150				CSA-500			
Tow.	Type	Zone	Max	Tow.	Type	Zone	Max	Tow.	Type	Zone	Max	Tow.	Type	Zone	Max
3012	C1	11-2	93.0	3063	C1	11-3	72.8	3063	C1	11-3	93.4	3063	C1	11-3	119.2
2873	C1	11-2	91.8	3015	C1	11-2	72.6	3062	C1	11-3	93.4	3062	C1	11-3	119.1
3091	C1	11-3	90.9	370	D1	1	72.6	3014	E1	11-2	84.6	3014	E1	11-2	105.9
3156	C1	11-4	90.4	31	D1	1	72.3	2967	E1	11-2	84.3	2967	E1	11-2	105.4
370	D1	1	90.1	3062	C1	11-3	71.9	370	D1	1	84.1	2949	E1	11-2	105.1
31	D1	1	89.5	557	D1	1	71.8	2949	E1	11-2	84.1	2821	E1	11-2	104.2
334	D1	1	89.3	334	D1	1	71.8	3015	C1	11-2	83.8	3068	D1	11-3	99.1
405	D1	1	89.1	3065	C1	11-3	71.5	2821	E1	11-2	83.5	3089	D1	11-3	98.7
865	D2	2b	88.7	106	D1	1	71.5	31	D1	1	83.4	3118	D1	11-3	98.1
557	D1	1	88.7	467	D1	1	71.5	334	D1	1	83.2	3146	D1	11-4	97.8
509	D1	1	88.5	348	D1	1	71.4	557	D1	1	82.8	370	D1	1	96.8
87	D1	1	88.4	87	D1	1	71.3	405	D1	1	82.7	334	D1	1	95.8
575	D1	1	88.3	3068	D1	11-3	71.2	509	D1	1	82.4	405	D1	1	95.6
106	D1	1	88.3	575	D1	1	71.2	168	D1	1	82.4	31	D1	1	95.6
264	D1	1	88.2	405	D1	1	71.1	87	D1	1	82.3	3015	C1	11-2	95.5
467	D1	1	88.2	509	D1	1	71.0	264	D1	1	82.3	264	D1	1	95.1
168	D1	1	88.2	168	D1	1	71.0	467	D1	1	82.3	509	D1	1	95.1
348	D1	1	88.2	3077	C1	11-3	70.9	106	D1	1	82.3	557	D1	1	95.1
315	D1	1	87.7	264	D1	1	70.8	348	D1	1	82.2	168	D1	1	95.0
2934	C1	11-2	87.6	729	D1	1	70.5	575	D1	1	82.2	2944	D1	11-2	94.8

[22] The 37 change-over tension towers in the PLS-Cadd models are not included in the results. It was verified separately that the towers are within the specified design range for angle, wind span and weight spans.

4.4 Foundations

The foundations in the LITL are conservatively designed using the maximum foundation force for each tower type on all towers. An additional overload factor was applied to the basic requirements in the CSA.

Figure 27 shows foundation comparison of guyed suspension towers, axial compression and shear forces. The specified loading used in the design of foundations ("As-Designed") is compared to maximum foundation reaction forces obtained in this study. Values from this study are assessed somewhat conservatively[23].

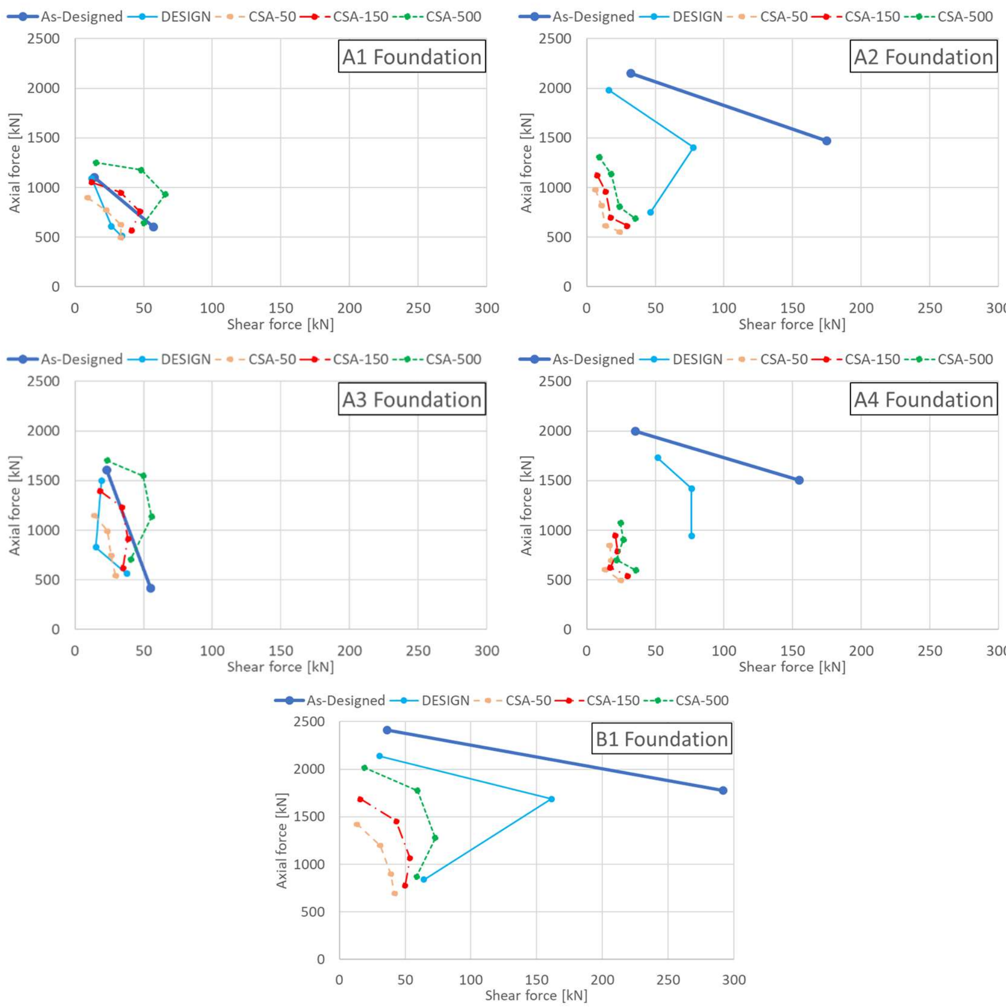

FIGURE 27 Maximum foundation forces in guyed suspension towers. Each figure shows: two load combinations used in the design ("As-Designed") and maximum combinations of the load cases "Max. ice", "Ice&wind", "Wind&Ice" and "Max. Wind" for each of the load groups: DESIGN, CSA-50, CSA-150 and CSA-500. All values are presented without strength factor.

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[23] Maximum axial force is combined with maximum shear force even though they are not in the same tower. Axial force in the load case "Max. Ice" was increased by 25% in order to compensate for possible additional effects in the load case "Unbalanced ice".

The results show that the foundation strength of guyed towers fulfill the DESIGN loading, CSA-50 and CSA-150 loading. Foundation strength is less than CSA-500 loading for tower types A1 and A3[24]. The utilization of tower foundations A2, A4 and B1 is low, the reason being that these towers are designed for rime ice while rime ice is not included in the CSA loading.

Figure 29 show a comparison of maximum axial tension and compression force in self-supported towers[25]. The foundation design loads ("As-Designed") is compared to maximum forces obtained in this study[26].

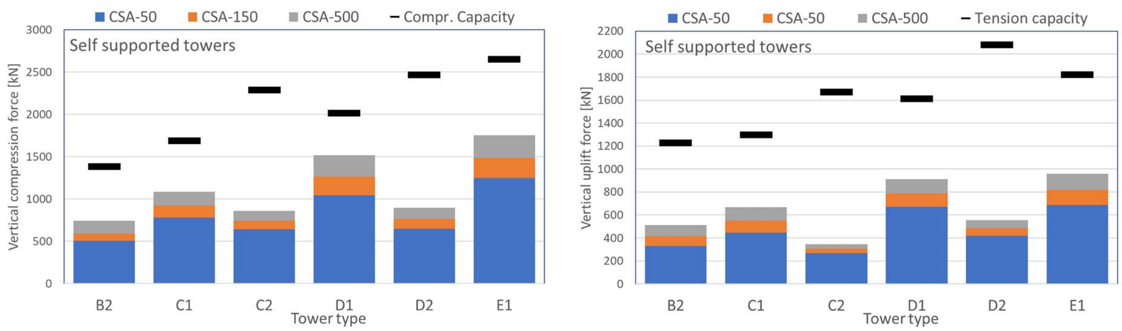

FIGURE 28 Maximum axial force on tower foundation in self-supporting towers[21] and comparison to force used in the design of foundations. The vertical compression force is to the left and vertical uplift force to the right.

The results show that the foundation of self-supported towers fulfills CSA-500 loading in all cases. The reason for why the "As-Designed" strength is much higher than the CSA loading is related to following factors: (i) Rime ice is not included in the CSA loading, (ii) Load cases related to security loading[27] (e.g. broken wire condition) are often critical.

Figure 29 shows a comparison of maximum guy forces used in the design of guys ("As-Designed") to the load cases used in this study. The guy forces are well below the "As-Designed" values, the reasons being: (i) Rime ice is not included in the CSA loading, it influences tower types A2, A4 and B1, (ii) Wire break is often critical load case for guy forces, it is not part of reliability loading.

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[24] It is usually conservative to assume linear strength curve between nodes.
[25] Self-supporting towers usually have the resulting force in direction close to the slope of the main leg member. They can be evaluated using only the vertical force when foundations are sloping in the same direction. Grillage foundations are sloping in the direction of the leg but some pile foundations are not following the same criteria.
[26] The 37 change-over towers in the PLS-Cadd models are not included in the comparison.
[27] This study considers only reliability loading. Refer to definitions.

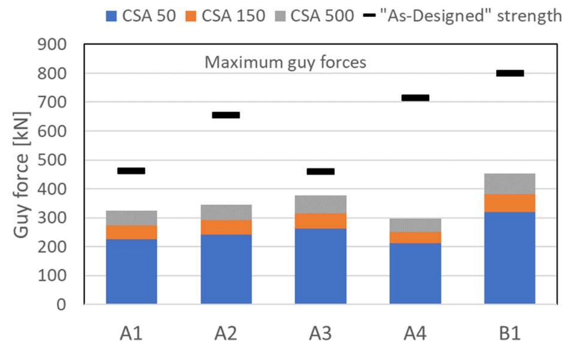

FIGURE 29 Maximum guy forces for each tower type in the analysis. The "As-Designed" values used in the design of all guys are shown with a black line and compared to DESIGN loading on the left figure and to the CSA loading on the right figure.

4.5 Conductors

This section summarizes the results of the utilization of all pole, electrode and OPGW conductors. Figures 30 to 32 presents the results of the analysis, showing the critically loaded conductor section utilization per zone. Table 7 shows the conductor specification (description) mechanical properties and characteristics for the pole conductor, the electrode conductor, and the OPGW.

The DESIGN loading cases result in utilization below 100% for the pole and electrode conductors throughout the line. The OPGW utilization is greater than 100% in two spans[28] each in zones 8b and 10 where the maximum utilization is 101.8% and 105.8% under "*Max ice*" load case.

The CSA-50 loading results in the utilization of less than 100% for all conductors in all zones.

The CSA-150 loading results in a utilization greater than 100% in for the OPGW in 5 zones (3b, 4a, 4b, 6, 10) with the highest utilization of 109.3% occurring under "*Ice and wind*" load case as shown in Table 22. Table 23 shows the utilisation of the OPGW per zone for the different load types. The pole and electrode conductors have utilization below 100% with the CSA-150 loading.

The CSA-500 loading results in utilization greater than 100% for the pole conductor in three zones (4a, 6, 11). The maximum utilization in these zones is 101%, 100.1% and 107.7% respectively. The electrode line utilization is exceeded in zone 3a by up to 113.7%. All other zones have sufficient strength to support the CSA-500 loading. The OPGW utilization exceeds 100% in ten zones when analyzed with the CSA-500 loading.

[28] Tower 2298-2300 and Tower 2108-2110

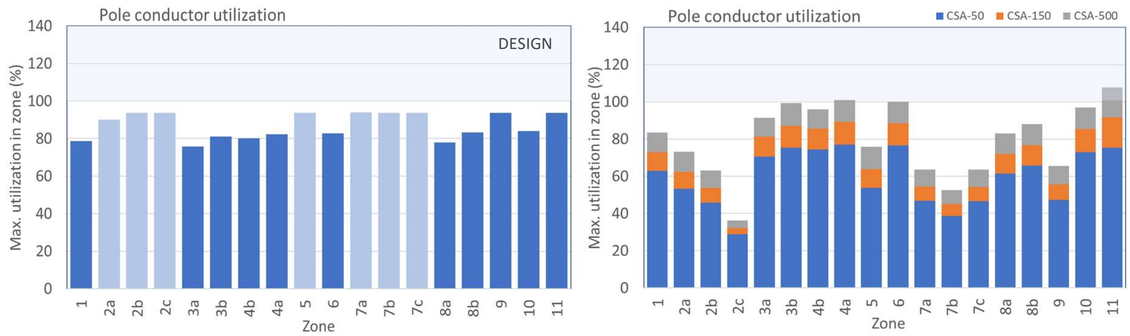

FIGURE 30 Pole Conductor, highest utilization in each loading zone. Utilization in DESIGN loading[21] is to the left and CSA loading to the right.

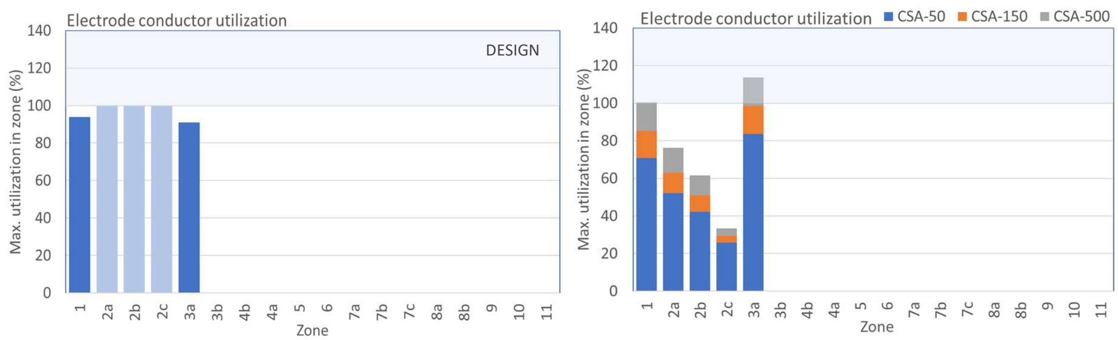

FIGURE 31 Electrode Conductor, highest utilization in each loading zone. Utilization in DESIGN loading[21] is to the left and CSA loading to the right.

FIGURE 32 OPGW Conductor, highest utilization in each loading zone. Utilization in DESIGN loading21 is shown to the left and CSA loading to the right.

TABLE 22. Utilization of conductors per loading type and load case.

	Ice + Wind	Max Ice	Max Wind	Wind + Ice	Max.
DESIGN		105,8	60,3	90,2	105,8
Electro		100,0	39,2	69,9	100,0
Opgw		105,8	39,2	90,2	105,8
Pole		93,8	60,3	85,8	93,8
CSA 50	88,7	86,6	41,0	59,9	88,7
Electro	83,5	81,8	39,5	57,2	83,5
Opgw	88,7	86,6	33,5	59,9	88,7
Pole	77,0	76,1	41,0	54,8	77,0
CSA 150	109,3	106,1	45,9	74,2	109,3
Electro	98,5	96,8	45,3	68,8	98,5
Opgw	109,3	106,1	37,5	74,2	109,3
Pole	91,6	90,1	45,9	63,3	91,6
CSA 500	132,8	128,7	51,5	90,9	132,8
Electro	113,8	111,7	51,4	82,4	113,8
Opgw	132,8	128,7	41,7	90,9	132,8
Pole	107,7	106,0	51,5	73,5	107,7

TABLE 23. Utilization of OPGW per zone and loading type.

ZONE	DESIGN	CSA 50	CSA 150	CSA 500
1	91.8	67.4	83.0	100.4
2a	83.5	43.7	52.6	63.1
2b	97.4	41.3	49.9	60.1
2c	91.6	21.8	24.2	26.9
3a	83.5	76.3	93.4	113.0
3b	96.6	87.9	108.4	131.9
4a	97.5	88.7	109.3	132.8
4b	93.8	85.5	105.1	127.4
5	93.5	49.2	59.6	71.9
6	97.2	88.1	108.5	131.9
7a	92.8	39.3	46.9	55.9
7b	100.0	35.9	42.9	51.1
7c	97.0	40.6	48.8	59.1
8a	94.1	69.8	85.8	103.8
8b	101.8	77.7	93.5	110.5
9	95.5	46.0	55.3	66.1
10	105.8	87.8	106.0	127.1
11	100.0	78.2	97.4	119.3

4.6 Insulators

This section presents the results of the utilization of the critically loaded insulator per zone. Figure 33 presents the results for the suspension insulators and Figure 34 for the tension insulators. For analysis of the suspension insulators, the utilization for the pole and electrode insulators are compared to determine the insulator with critical loading. This implies that one zone may have the suspension electrode insulator with maximum loading while in the next zone, the pole conductor insulator could be critically loaded.

Table 8 and Table 9 present the strength of insulators and hardware strings used on the LITL.

The suspension insulators can withstand the DESIGN loads in all sections excluding one tower in section 11-2 where the pole conductor insulator utilization is 103.7%. The increased load reduces the safety factor[29] by 4%. All pole and electrode conductor tension insulators can support the DESIGN loads with the highest loaded insulators located in zones 7b and 11.

With the CSA-50 and CSA-150 loading, all pole and electrode conductor insulators (suspension and tension) are sufficiently strong to withstand the loads with the highest loaded insulator located in zone 11.

The suspension insulators have capacity to withstand the CSA-500 loading in 97.5% of the towers. Seventy tower insulators have a maximum utilization up to 114%. The tension insulators can withstand the CSA-500 loading in 91% of the towers. Twenty-nine tower insulators have a utilization up to 117%.

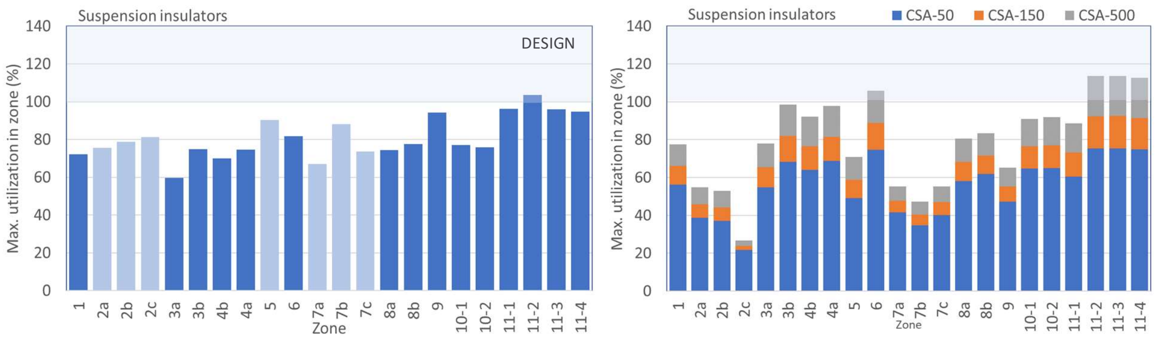

FIGURE 33 Suspension insulators, highest utilization in each loading zone. Utilization in DESIGN loading[21] is to the left and CSA loading to the right.

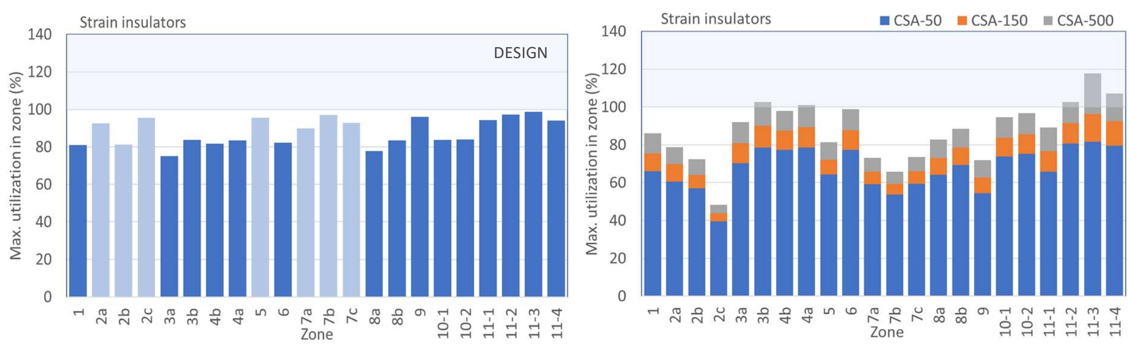

FIGURE 34 Tension insulators, highest utilization in each loading zone. Utilization in DESIGN loading[21] is to the left and CSA loading to the right.

4.7 Hardware

The capacity of the tension hardware was assessed by comparing the maximum conductor tensile force for each load type per zone to the tensile capacity of the hardware including the safety factor of 1.44[30]. The suspension hardware capacity was assessed by comparing the maximum resultant loads from PLS-Cadd to the hardware capacity including the safety factors.

The line design criteria [7] states that the strength of the tension hardware assembly must be rated at 1.15x the RTS of the conductor (Table 13), which the LITL pole, OPGW and electrode hardware meets.

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[29] Safety factor of 2 equals a strength factor of 0.5

[30] Requirement for tension is 1.15 x RTS of conductor. Max conductor utilization is 80% of RTS. (1.15/0.8=1.44)

The pole conductor hardware is rated at 17% more than the RTS of the conductor with the critical component being the turnbuckle, see values in Table 7 and Table 9.

4.7.1 Pole conductor hardware

Figure 35 and Figure 36 present the results of the critically loaded pole hardware for the tension and suspension assemblies per zone. The results show that the tension hardware is suitable for the DESIGN loads, CSA-50 and CSA-150 loading. The suspension hardware is suitable for the DESIGN loads except for one tower[31] in zone 11 where the utilization is exceeded by 3%. This results in the hardware safety factor being reduced by 3%[32].The suspension hardware is suitable for CSA loads up to CSA-150 loading. With CSA-500 loading, the utilization of nine towers (0.3% of all suspension towers) in zones 6 and 11 is exceeded by up to 13%.

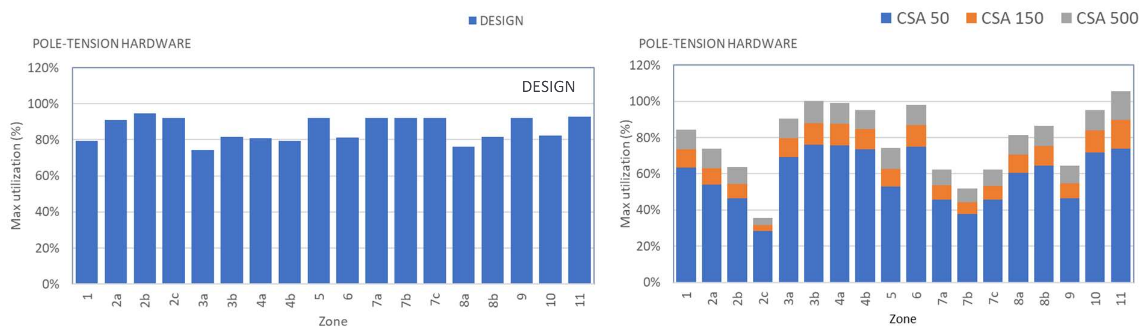

FIGURE 35 Pole conductor tension hardware. Maximum utilization per zone of DESIGN[21] loading (left) and CSA- loads (right) is presented.

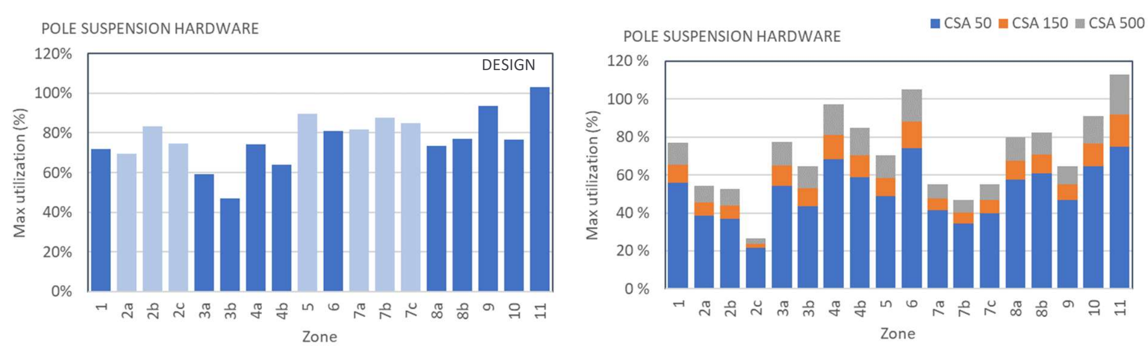

FIGURE 36 Pole conductor suspension hardware. Maximum utilization per zone of DESIGN[21] loading (left) and CSA- loads (right) is presented.

[31] Tower 2918

[32] Safety factor reduced from 2 to 1.94

4.7.2 Electrode conductor hardware

Two strengths of suspension hardware are used for the two types of electrode conductors as reflected in Table 9. The electrode suspension hardware is over utilized when the safety factor of 2 is applied as per the design specification, see Table 13. An analysis was done to establish the safety factor that would result in the hardware being utilized within limits. Figure 37 presents the safety factors for each loading type and zone. The graph indicates that the minimum safety factor for the DESIGN case is 1.5. A safety factor of 1.5 results in utilization of the suspension hardware below 100%. The suspension clamp is the weakest component in the assembly.

Figure 38 presents the results of the critically loaded electrode tension hardware assemblies per zone. The results show that the tension hardware for the electrode conductors has a utilization exceedance of 5% for zones 2a,2b,2c with the DESIGN loads. The tension hardware is suitable for CSA loads up to CSA-500 loading.

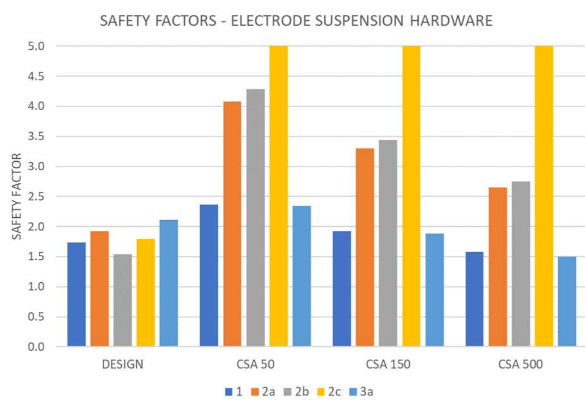

FIGURE 37 Safety factors for electrode suspension hardware per loading type for each zone.

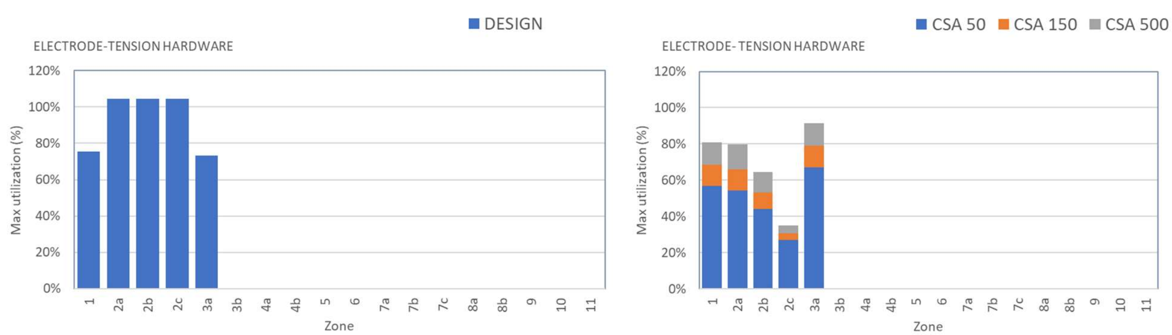

FIGURE 38 Electrode conductor tension hardware. Maximum utilization per zone of DESIGN[21] and CSA- loads is presented.

4.7.3 OPGW hardware

Figure 39 and Figure 40 present the results of the critically loaded OPGW hardware for the tension and suspension assemblies per zone.

The results show that the OPGW tension hardware is suitable for the DESIGN loads and up to CSA-150 loading. The tension hardware utilization in zone 11 is exceeded by 10% with the CSA-500 loading while utilization in the remaining zones is less than 100%.

The OPGW suspension hardware is suitable for the DESIGN loads and up to CSA-150 loading. With the CSA-500 loading, the suspension hardware utilization is exceeded in 4 zones.

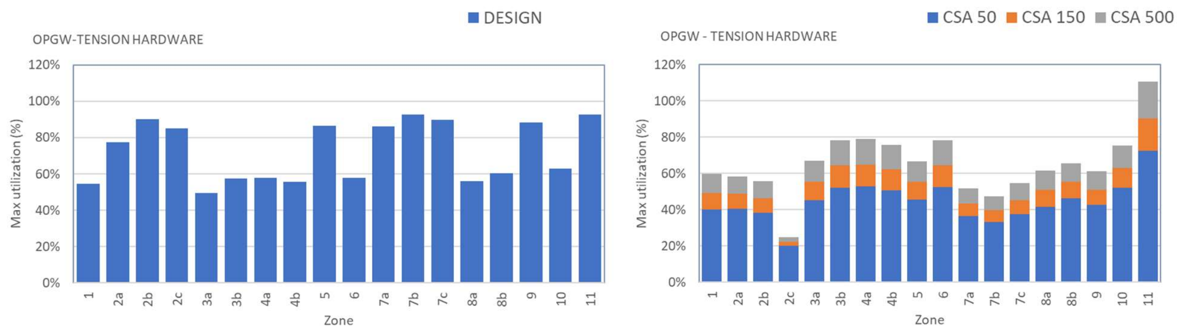

FIGURE 39 OPGW tension hardware. Maximum utilization per zone of DESIGN[21] and CSA- loads is presented.

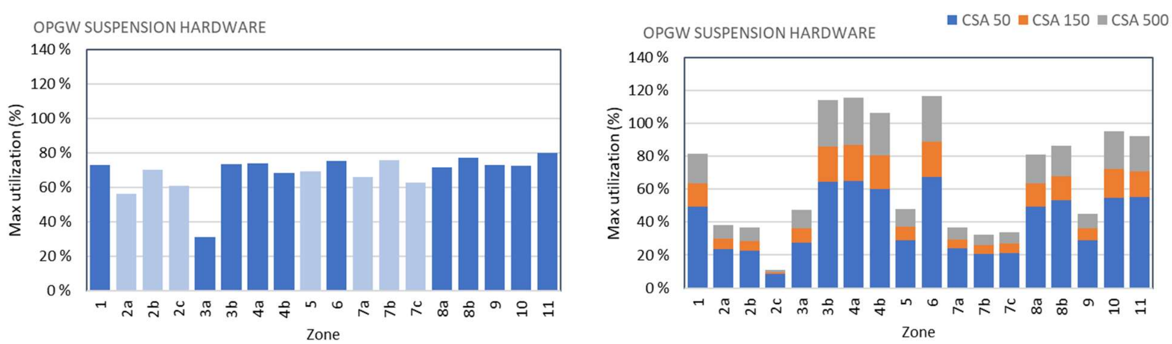

FIGURE 40 OPGW suspension hardware. Maximum utilization per zone of DESIGN[21] and CSA- loads is presented.

5 DISCUSSION OF RESULTS

This section presents a summary of the results of the analysis as well as an interpretation of the results. The CSA loading does not include rime icing nor does it provide recommended values on this load type. Comparison of results presented here for "benchmarking" strictly relates to loads derived for glaze icing for all sections including the sections that belong to rime ice area (2, 5 and 7). However, for these sections that belong to rime ice area, the results of the analysis show significantly higher utilization compared to results determined under CSA loads. A separate study will be conducted in the next phase to update the rime ice load values for the LITL as well the capacity assessment under rime ice. In determining the rime ice load effects, enhanced numerical models will be used that will account for local effects of the terrain.

5.1 Suspension Towers

All suspension towers have sufficient structural capacity when analyzed with the CSA-50 loading and DESIGN loads. With the CSA-150 loading majority of the suspension towers are below 80% utilization and eight towers have a maximum utilization up to 104% in zone 3a and 11-4 under "*Wind + Ice*" load case. The approach for ice load on the tower members was conservative when compared to the CSA requirements. When the CSA requirements was applied, the maximum utilization drops from 104% to 100.8%. The number of overutilized towers is reduced to three. The tower utilization with the CSA-500 loading is high for all load cases with the highest utilization of 135%.

Overall it can be concluded that the suspension towers are close to fulfilling requirements with CSA-150 loading, with a marginal exceedance of utilization in zones 3a and 11-4 where three towers have utilization exceedance up to 0.8%. The most critical section is between tower no. 1216-1228 in zone 3a and 3212 and 3219 in zone 11-4.

5.2 Tension Towers

Results shows that all tension towers are fulfilling requirements in CSA-150 loading. When the CSA-500 loading is applied, six tension towers in zone 11 exceed 100% utilization.

5.3 Foundations

The foundations in the LITL are conservatively designed using the maximum foundation force for each tower type on all towers. An additional overload factor was applied to the basic requirements in the CSA.

The results show that the foundation strength of guyed towers fulfill the DESIGN loading, CSA-50 and CSA-150 loading. Guy anchors fulfill CSA-500 loading in all cases.

Foundation of self-supported towers fulfills CSA-500 loading in all cases.

5.4 Conductors

The pole and the electrode conductors have sufficient strength capacity under DESIGN loading with utilization below 100% of allowable capacity. Four spans of the OPGW have a utilization exceedance of 5.8% (120kN or 84.5% of RTS) under "*Max Ice*" load case in DESIGN loading. The spans were initially strung to the maximum stringing tensions but later marker balls (aircraft warning spheres) were installed on the OPGW. The combination of the high stringing tension, presence of marker balls and hardware accessories in addition to the design climatic loads, contribute to the utilization exceedance. The corresponding increased sag has no significant impact on the internal and external clearances.

All conductors have sufficient strength capacity with the CSA-50 loading. With CSA-150 loading, the utilization of the electrode and the pole conductor is within limits, but the OPGW exceeds the limits in five loading zones with maximum exceedance of 9.3% (124kN) under *Ice and Wind*" load case. The CSA-500 loading results in all cables with utilisation above CSA limits in some zones and hence is not discussed further.

The OPGW was subjected to "Ultimate tensile strength tests" during "type testing" of the cable and three "routine tests" on three production batches. All tests exceeded the rated tensile strength of the cable between 9.7% and 20% [12]. The "Strain Margin" type tests [12] indicate that the optical fibres permanent attenuation in signal was below the limits specified in IEEE Std. 1138-2009 when tested up to the RTS. The OPGW is used for telecommunications and operation of the powerline and has two backup systems in the form of a radio link and telephone lines.

Overall it can be concluded that the strength capacity of the pole and electrode conductors is sufficient for DESIGN loading and up to CSA-150 loading. The OPGW utilization is exceeded by up to 5.8% in two spans when loaded with the DESIGN loads. With the CSA-150 loading, the OPGW utilization is exceeded in five zones by up to 9%. The increased utilization of the OPGW may lead to permanent elongation however it is within the failure limit and should not break or result in a line outage.

5.5 Insulators

The suspension and tension insulators for the electrode and pole conductors have sufficient strength capacity to withstand the CSA-50 and CSA-150 loading. The DESIGN loads result in one tower where the suspension insulator load limit is exceeded by 4%. This is not considered critical as the design uses a safety factor of 2[33]. The insulators fulfill the strength requirements with CSA-500 loading in most zones. Zone 11 has the highest insulator utilization with up to 17% exceedance.

Overall the suspension and tension insulator strings for the electrode and pole conductors fulfill the strength requirements with DESIGN loads, CSA-50 and CSA-150 loading.

5.6 Hardware

The tension assemblies for the OPGW and pole conductors have sufficient capacity to support the DESIGN loads and up to CSA-150 loading. The electrode tension hardware utilization exceedance is 4% with DESIGN loading in the rime ice zones. A detailed rime ice study will be conducted, and the results will be updated. The electrode tension hardware has sufficient capacity for CSA 50 loading and loads

[33] Safety factor is reduced from 2 to 1.94

up to and including CSA-500 loading. With CSA-500 loading, zone 11 has utilization exceedance of 10% for the Pole and OPGW tension hardware.

The electrode suspension hardware utilization was exceeded when evaluated with a safety factor of 2. The maximum possible safety factor with the DESIGN loads is 1.5. A safety factor of 1.5 to 1.7 is generally utilised in hardware design. All other suspension hardware was evaluated with a safety factor of 2 corresponding to the design requirements.

The Pole and OPGW conductor's suspension hardware have sufficient strength capacity to support the DESIGN loads, CSA-50 loads and up to CSA-150 loading. The pole conductor hardware of one tower in zone 11 has utilization exceedance of 3% with the DESIGN loads[34]. All suspension hardware has utilization exceedance with CSA-500 loading.

Overall the tension and suspension hardware for the pole conductors and OPGW fulfill the strength requirements with DESIGN loads and up to CSA-150 loading. The electrode conductor and suspension hardware safety factor is reduced to 1.5 with the DESIGN and is approximately 2 under CSA-150 loading. The electrode tension hardware has an exceedance of 4% with the DESIGN load due to the rime ice loading but has sufficient capacity for CSA-50 loads and loads up to CSA-500 loading.

Hardware is exposed to fatigue and wear due to Aeolian vibration and galloping. Aeolian vibration was considered in selecting the initial stringing tensions for the conductors and the line is fitted with vibration dampers on all conductors. Galloping clearance studies were completed by the designers of the line to establish the tower top geometry. The scope of this study did not include the influences of vibration and galloping.

[34] Safety factor reduced from 2 to 1.94

6 CONCLUSION

This study evaluates the "as-design" structural capacity of the LITL with respect to requirements specified in the Canadian Standard CSA 60826-10. The assumptions and design criteria developed by the designers were used in the assessment. Changes were made where the criteria differed from the CSA requirements. Climatic load (wind, ice and combined wind and ice) with 50-years, 150-years and 500-years return periods as defined in CSA 60826-10 were used in the analysis and compared against the design loading. The capacity level with a 50-years return period should be regarded as a reference capacity level, whereas the higher capacity levels are to be understood as relative to the reference one[35]. The results of the analysis include rime ice loading in DESIGN loads in some loading zones but not in the CSA loading. A separate study will be conducted on the rime ice and the utilization values for the affected zones will be updated.

Table 24 presents a summary of the key findings of the study regarding the following questions that were raised in chapter 1:

- What is the "as-designed" structural reliability concerning CSA requirements?
- Which sections have the lowest structural capacity concerning CSA requirements?
- Which components in the LITL line are critical concerning the structural models used?

TABLE 24. Summary of strength capacity of components.

COMPONENT		CLIMATIC LOADING				COMMENTS
		DESIGN	CSA-50	CSA-150	CSA-500	
Towers	Suspension	Yes	Yes	~ Yes	No	With CSA-150 loading, three towers on the line have a utilization exceedance up to 0.8%[36]. With CSA-500 loading the utilization exceedance is 36%.
Towers	Tension	Yes	Yes	Yes	No	Six towers have a utilization exceedance up to 19% with CSA-500 loading.
Conductors	Pole	Yes	Yes	Yes	No	With CSA-500 loading, utilization exceedance is 8% in zone 11.
Conductors	Electrode	Yes	Yes	Yes	No	With CSA-500 loading, zone 3a has utilization exceedance of 14%.

[35] Reliability level 2 (150-years return period loads) is three times more reliable than level 1 (50-years) and reliability level 3 (500-years return period loads) is 10 times more reliable than level 1.

[36] This value is based on CSA ice load applied to the tower body. With CSA-150 loading, and more conservative ice loads applied to the tower body as per the DESIGN, eight towers on the line have a utilization exceedance up to 4%.

COMPONENT		CLIMATIC LOADING				COMMENTS
		DESIGN	CSA-50	CSA-150	CSA-500	
	OPGW	~ Yes	Yes	No	No	OPGW utilization is exceeded up to 6% in 4 spans under "max ice" with DESIGN loads. Five zones have utilization exceedance up to 9% with CSA-150 loads. The strength capacity corresponds to approximately 90 years return period of loading[37].
Insulators	Suspension Pole and Electrode	Yes	Yes	Yes	No	With the CSA-500 loading, 71 suspension and 29 tension towers insulators have a utilization exceedance up to 17%.
Insulators	Tension Pole and Electrode	Yes	Yes	Yes	No	With CSA-500 loading, the tension insulator utilization is exceeded in few zones.
Hardware	Pole	~ Yes	Yes	Yes	No	The pole suspension hardware of one tower has a utilization exceedance of 3% in zone 11 under DESIGN loading. CSA-500 loading, results in utilization exceedance for the POLE conductor hardware in few zones.
Hardware	Electrode	~ Yes	Yes	~ Yes	No	The rime ice zones in DESIGN loading leads to 4% exceedance in tension hardware and a reduction in the suspension hardware safety to 1.5[38]. The rime ice loading will be studied later. The CSA-150 loading results in a safety factor of approximately 2 for the suspension hardware.
Hardware	OPGW	Yes	Yes	Yes	No	With CSA-500 loading, tension hardware utilization is exceeded in zone 11 and the suspension hardware in 4 zones.
Foundation	Guyed tower (susp.)	Yes	Yes	Yes	No	A1 and A3 tower foundations utilization is exceeded with CSA-500 loading
Foundation	Self-supported Towers	Yes	Yes	Yes	Yes	
Foundation	Guy anchoring	Yes	Yes	Yes	Yes	

When evaluating the overall capacity of the LITL, the utilization of components is not equally important due to the failure sequencing which is controlled by varying the selection of the component strength factors. The suspension towers are defined in the design requirements as the most critical component in the LITL with the lowest safety factors, hence they should be the first to fail.

Overall the LITL is close to fulfilling the CSA-150 loading with the following exceptions:

[37] The return period was estimated based on analysis of CSA-50, CSA-150 and CSA-500 loading using curve fitting.
[38] There is a discrepancy between the initial design requirements and the actual design with respect to the safety factor used for the suspension hardware. The hardware drawings suggest that a decision was taken to reduce the safety factor however no formal documentation was available for this study.

- Three suspension towers have utilization exceedance up to 0.8% in zone 3a and zone 11-4 towers with "*Wind and Ice*" loading.
- The OPGW conductor has utilization exceedance up to 9% in the load case "*Ice and Wind*" in zones 3b, 4a, 4b, 6 and 10. The maximum utilization in the study was set at the damage limit of 80% of RTS. The increased utilization may lead to permanent elongation however it is within the failure limit and should not break or result in a line outage. It may be possible to accept a higher utilization value in few spans provided it is well below the failure limit[39]. The strength capacity corresponds to approximately 90 years return period of loading.
- The electrode conductor suspension hardware fulfills a safety factor is 1.88 instead of 2. The specified safety factor of 2 is considered high compared to normal design practice. This only presents a marginal increase in the risk of failure.

The above-mentioned exceptions will be considered in more detail in the overall reliability study of the LITL.

Other factors that may influence the overall line performance

Conductors and hardware may be subjected to fatigue and wear due to Aeolian vibration and galloping. It was not part of this study to evaluate fatigue and wear. It can though be stated that background documents for the design show that Aeolian vibration was studied in some detail and conductor stringing tension was chosen according to recommendations from industry experts considering best practices and past experiences. The line is protected with dampers and the determination of clearance requirements and line configuration selection considered galloping criteria. However, the line does not have anti-galloping devices because this is a random phenomenon, and should this happen, the appropriate mitigation measures can be taken.

Proposed future work

The following work can be undertaken to improve the understanding of the strength capacity of the line and its critical components

- Complete an updated rime ice study and strength assessment of the key components
- Assess the impact of an OPGW failure on the suspension towers when subjected to heavy ice loads. The effect of impulse loading on the tower must be assessed when the OPGW fails to understand the level of failure that can be expected. Will the failure cause an entire tower failure or simply a failure of the earth peak?

[39] The OPGW has been successfully type tested to 109% of RTS however this value is not guaranteed by the manufacturer.

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