Undertaking Request (U-99)

Transcript Reference: August 7, 2018, Pg. 139, line 20 to Pg. 140, line 7

Re: Christensen Report

Undertake to file the report that you referred to that contains the benchmarks for O & M costs. *(Christensen Report referenced in oral testimony)*

Undertaking Response

Please refer to U-99, Attachment 1 (Transmission O&M Cost Benchmark Study).

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MEMORANDUM

TO: Kevin Fagan, Newfoundland and Labrador Hydro

FROM: David Armstrong, Robert Camfield, Nick Crowley

DATE: April 12, 2018

SUBJECT: Transmission O&M Cost Benchmark Study

INTRODUCTION

Benchmarks for Newfoundland and Labrador Hydro (Hydro) transmission O&M costs are presented below. The study is mainly focused on the O&M costs for Hydro's existing high voltage AC transmission network. The study also provides a range of reasonableness for the expected O&M costs for Labrador Transmission Assets (LTA) and Labrador-Island Link (LIL).

Cost benchmarks provide a means to gauge cost performance, and it is common for electric utilities and regulatory authorities to compare and benchmark costs across regions. Historically, the concern over cost and price levels has mainly been an issue for generation services. This is as expected: For some time, the all-in costs of transmission services were a comparatively minor share of the prices of bundled retail service. However, transmission over recent years has assumed an increasingly prominent role, in three ways: the conditions and prices for access to wholesale markets; cost allocation, which often assumes who benefits—who pays dimensions; and transmission cost levels. Transmission costs across virtually all regions of North America have risen dramatically since the early 2000s. The increase in the costs of transmission services is a direct consequence of four factors: major investment for interconnection with new generation, including renewable facilities; accommodation of changing flow patterns across regional networks; increased capacity to satisfy the long-term secular rise in electricity demand; and replacement of aging infrastructure approaching the end of its useful life.[1]

Played out in regulatory proceedings, transmission cost levels can become salient and contentious issues, and it is useful to gauge where things stand beforehand. To this end, the immediate cost study

[1] The rate of replacement of aging facilities would seemingly assume a steady state of reinvestment. However, casual inspection suggests a stark counterpoint: the rate of investment transmission in the North American departs significantly from a steady state. That is, the annual rate of investment in transmission remained at remarkably low levels during the mid-80s to the early-2000s, followed by dramatic increases in investment beginning in 2002/2003.

benchmarks transmission operations and maintenance (O&M) costs, which can be a sizable share of the all-in costs of transmission.[2]

The cost benchmarks for Hydro's existing AC transmission network are based on the observed operating cost levels of the transmission systems of Canadian and U.S. utilities. O&M costs of individual facilities are idiosyncratic, reflecting the numerous factors that influence cost levels. For this reason, the O&M cost estimates for LTA and LIL are likely to be less definitive. This is particularly the case for high voltage direct current (HVDC) facilities. For HVDC systems such as LIL, and operating costs for the converter stations are a major concern.

To summarize, transmission O&M cost levels explored in this study are as follows:

- *O&M COSTS FOR HYDRO'S TRANSMISSION AC NETWORK:* Transmission O&M cost levels of Hydro, in total, are benchmarked to those of Canadian and U.S. utilities. Hydro's transmission O&M costs are compared to the transmission costs of two samples of electric utilities, including five Canadian utilities and 24 U.S. utilities. The Canadian utilities include AltaLink, ATCO Electric, BC Hydro, Hydro-Quebec, and SaskPower. The sample of U.S. utilities is drawn from the population of investor-owned U.S. electric utilities according to load density broadly comparable to that of Hydro.

- *O&M COSTS FOR LTA FACILITIES*: O&M cost estimates for LTA are developed separately for route facilities (lines, towers, and equipment) and for terminal equipment, hereafter referred to as Station Equipment. O&M cost estimates for both Lines and Station Equipment are drawn from the observed O&M costs of the sample of U.S. utilities during 2016.

- *O&M COSTS FOR LIL HVDC FACILITIES*: Estimates of O&M costs for HVDC are also estimated separately for route facilities (lines, towers, and equipment), and for DC/AC converter facilities.[3] O&M cost estimates for lines, towers, and related equipment, hereafter referred to as Lines, are drawn from the observed O&M costs of a sample of U.S. utilities during 2016. O&M costs for substation/converter facilities are estimated, as observed O&M costs for HVDC converter facilities are not generally reported within the public domain.

STUDY RESULTS – TRANSMISSION O&M COST BENCHMARKS

Transmission O&M Cost Benchmarks for Hydro's AC Network.

Benchmark results for Hydro's overall transmission O&M cost level are reported below.

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[2] For the sample of utilities included in this study, transmission fixed O&M plus an allocated share of administrative overheads approximate 26% and 32% of the total financial costs of transmission, for the Canadian and U.S. utilities respectively.

[3] The converter facilities of HVDC systems assume two functions: the conversion of alternating current (AC) to direct current (DC) with rectifier technologies (rectifiers), and the inversion of DC to AC. Converter facilities that carry out the inversion function (inverters) often provide real-time system monitoring and control, and will also have fast responding voltage control equipment, harmonic filters, and other equipment that contribute to system-wide reliability.

TRANSMISSION O&M COST BENCHMARKS FOR NEWFOUNDLAND-LABRADOR HYDRO'S AC GRID

TRANSMISSION O&M COST per FACILITY MILE (CAD)						
	Average			*Variation*		
	Mean	Distance-Weighted	Median	*S.D.*	*Min*	*Max*
	Comparable U.S. Electric Utilties*					
Year						
2014	$11,647	$10,004	$10,277	$6,977	$3,897	$32,701
2015	$14,430	$12,146	$11,429	$9,499	$4,908	$42,628
2016	$15,497	$13,014	$13,016	$11,212	$5,419	$52,690
	Canadian Electric Utilties*					
2016	$12,961	$15,785	$11,146	$8,234	$4,691	$23,110
	Newfoundland Labrador Hydro					
Year	Total FOM Cost including A&G (000's)			FOM per Facility Mile		
2014	$19,205,435			$7,294		
2015	$21,801,680			$8,280		
2016	$17,270,649			$6,559		

* The U.S. and Canadian samples consist of 24 and 5 utilities, respectively.

Stated on a line-mile basis, the average transmission O&M cost levels for the U.S. and Canadian utilities are similar, with costs for the Canadian utilities somewhat below the transmission O&M cost levels for the U.S. utilities. Though a much larger group – 24 utilities in total – the U.S. sample includes three utilities with exceptionally high transmission O&M cost levels. For 2014-2016, this results in a notable difference between the sample means and medians, ranging from $1,816 to $2,136 per facility mile for the Canadian and U.S. samples respectively.

The analysis clearly demonstrates that transmission O&M cost levels for Newfoundland and Labrador Hydro are highly favorable. For years 2014-2016, the mean and median of transmission O&M cost level for the U.S. utilities average $13,858/mile and $11,574/mile respectively, and $11,721 on a distance-weighted basis. For these years, transmission O&M costs for Hydro are $7,377 per mile. Further to this point, Hydro's transmission O&M costs are 0.46 and 0.74 standard deviations less than the average of the distance weighted and median average measures[4] for the US and Canadian samples respectively,[5] and not far removed from the 2014-2016 minimum of the U.S. utilities, $4,741/mile.

[4] This varies from standard procedures, which call for statistical variance to be measured with respect to the sample mean.

[5] Of note, the dispersion of the average O&M costs for both samples is quite large.

Similarly, the 2016 mean and median of transmission O&M costs for the Canadian utilities are $12,960/mile and $11,150/mile respectively, compared to Hydro's cost level of $5,559/mile, also for 2016. Similar to the comparison with U.S. utilities, Hydro's transmission O&M costs are 0.80 standard deviations less than the observed median O&M cost level across the sample of Canadian utilities.

O&M Cost Estimates for Labrador Transmission Assets.

The Labrador Transmission Assets facility is a two circuit 315kV facility on a common right-of-way of 250km length. In operating status, we anticipate that the LTA facility will be capable of transmitting approximately 700MW.[6] The cost estimates are developed on a per-mile basis for Lines, and a per-MW basis for LTA Station Equipment situated in the Churchill Falls and Muskrat Falls switchyards. As mentioned, O&M cost estimates for the LTA are based on the operating costs for Stations Equipment for the sample of 24 U.S. utilities, as reported during 2016.[7]

The Lines-related O&M costs of the sample of U.S. utilities reflect dual circuits on common towers and multiple circuits on common routes. This implies that scale economies associated with common towers and common routes are accounted for. But not all across-system transmission circuits are multiple.[8] It is thus appropriate to adjust the U.S. sample-based O&M costs, while also recognizing the likely realization of economies of scale within the operation of LTA facilities, particularly within maintenance activities. Accordingly, LTA O&M cost estimates reflect the product of the O&M costs of the U.S. sample stated in terms of CAD/mile and the LTA circuit miles (310 miles), adjusted for *common route factors*, a form of scale economies, of 0.8 and 0.6 for low and high range cost estimates, respectively. O&M cost estimates for the LTA are as follows:

(see following page)

[6] For various voltage classes, the transfer capability of AC circuits can be estimated as a function of the surge impedance loading (SIL) and circuit length (miles). The estimate of 700MW for LTA is based on an inspection of a graphical representation of SIL, by voltage class. This result was confirmed by Hydro's technical experts, who anticipate that the operating limits for the LTA will likely reside within the 618MW – 800MW range. Operating capability of individual transmission facilities reflect contingency events and can often be considerably lower than nameplate MVA capacity.

[7] Costs reported for 2016 can be adjusted for annual cost inflation of 2.1% over the 2016-2018 period.

[8] High voltage transmission facilities in Western Europe can have as many as six circuits on a common set of towers.

O&M COST BENCHMARKS FOR LTA[9]

Benchmark Estimates of O&M Costs, Based on U.S. Sample		
	Low	High
Lines, Towers ($/Mile)	$8,783	$12,910
Station Facilities ($/MW-year)	$4,060	$6,226
Benchmark Estimates of O&M Costs, LTA Facilities		
	Low	High
Lines, Towers	$1,637,282	$2,807,683
Stations	$2,842,325	$4,358,231
Total O&M	$4,479,606	$7,165,914

The estimated operating costs for LTA are substantially less than the expected operating cost level for LIL reviewed next, for two reasons. Lines-related O&M costs are largely a function of transmission distances; Lines facilities of LIL have two times greater length than the counterpart facilities of the LTA. Second, the equipment and functionality of the Stations Equipment of the LTA are conventional AC technologies, and are thus likely to be dramatically less costly than the converter facilities of the LIL HVDC system.[10] Indeed, the estimates of O&M costs for the Stations Equipment of the LTA are approximately one-fourth that of Labrador-Island Link.

O&M Cost Estimates for Labrador-Island Link.

Labrador-Island Link is 350kV facility capable of transmitting 900MW of power over a distance of 1,100km. As discussed, O&M cost estimates for the Labrador-Island Link are estimated separately for Lines and converter facilities. The cost estimates reflect the serious limitations of available data: operating expenses for HVDC facilities do not appear to be available in the public domain. Second, HVDC technologies are undergoing further development, mainly in the design schemes and installed equipment within converter facilities. Whereas the features and equipment of Line facilities are more-or-less common to all power systems, the capability and functionality of converter facilities can vary in substantial ways. Thus, the O&M cost estimates for the Lines facilities, shown below, are likely to be more reliable and accurate than the O&M cost counterparts for converter facilities. However, the costs of converter facilities often constitute a fairly large share of the all-in O&M costs of HVDC systems. Accordingly, potential estimation error for

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[9] LTA Line-related O&M cost estimates ($LTA^{Lines}_{O\&M}$) are determined as follows:

Cost/Mile: $EV(LTA^{Lines}_{O\&M}/mile) = (O\&M_{USD}/mile)_{US\ Sample,\ 2016} * (CAD/USD) * Inflation_{2019\text{-}2016}$

LTA Cost/Mile Range: Low Range $LTA^{Lines}_{O\&M}/mile = EV(LTA^{Lines}_{O\&M}/mile) - 0.25*SD(LTA^{Lines}_{O\&M}/mile)$

High Range $LTA^{Lines}_{O\&M}/mile = EV(LTA^{Lines}_{O\&M}/mile) + 0.25*SD(LTA^{Lines}_{O\&M}/mile)$

LTA Cost Range: Low Range $LTA^{Lines}_{O\&M}$ = Low Range $LTA^{Lines}_{O\&M}/mile * route\ miles * (circuit\ multiple - common\ route\ factor_{High\ Range})$

High Range $LTA^{Lines}_{O\&M}$ = High Range $LTA^{Lines}_{O\&M}/mile * route\ miles * (circuit\ multiple - common\ route\ factor_{Low\ Range})$

[10] Benchmark investment costs for the converter facilities for large-scale HVDC lines can approach $500 million CAD. Investment and operating costs are strongly hinged on the functional capability which, as briefly discussed later, can include advanced control functions, black start capability, and often includes synchronous condensers in the case of line commutation converter technologies.

the costs converter facilities carries over to the overall O&M cost estimates for Labrador-Island Link. That is, the O&M cost estimates for LIL may have considerable estimation error.

Cost estimates for the Labrador-Island Link are reported below:

O&M COST BENCHMARKS FOR LABRADOR-ISLAND LINK[11]

Benchmark Estimates of O&M Costs, HVDC Facilities		
	Low	High
Lines, Towers ($/mile)	$8,005	$11,281
Converter Facilities ($/MW)	$13,228	$19,787
Benchmark Estimates of O&M Costs, Labrador Island Link		
	Low	High
Lines and Towers	$5,471,285	$7,710,426
Converter Facilities	$11,905,459	$17,808,622
Total O&M	$17,376,744	$25,519,048

As presented above, O&M cost estimates for HVDC facilities are likely to be substantially above those of conventional AC facilities, despite the long distances typically involved in DC facilities. Our research suggests that Lines equipment and facilities for HVDC systems are likely to approximate the costs of AC networks, and are perhaps somewhat less because of lower "facility content". Also, operations of HVDC systems may realize scale economies compared to AC facilities because of the longer transport distances. Accordingly, O&M costs for HVDC Lines are likely to be somewhat less than AC facilities of similar length and operating environment, stated on cost per mile basis. This leaves converter facilities: O&M cost differences between AC and DC appear to reside exclusively with the conversion equipment and stations of HVDC systems.

This investigation has revealed that the converter facilities of HVDC systems provide several capabilities of high value beyond the provision of power transfer over extended distances with low losses, for which HVDC systems are commonly known. First, HVDC control equipment can improve overall, system-wide reliability, obtained through fast-responding power supply including, depending on equipment and functionality, black start capability. Second, major reliability benefits can be realized when HVDC systems are paired with large-scale hydro generation. Under selected circumstances, fast-responding capability of hydraulic generation, controlled through HVDC converter facilities, can provide the means of satisfying standards of transient stability and, in so doing, increasing the overall transfer capability of AC meshed networks across regions.[12] These expanded capabilities reduce capital and operating expenditures within

[11] Cost estimates do not incorporate adjustment for observed and expected inflation. Such adjustment is arguably appropriate insofar as the observed O&M costs of Manitoba's Dorsey station, which reflects 2015 experience, are used as the basis for O&M cost estimates for converter facilities.

[12] Transient stability studies conducted by Manitoba Hydro (MH) suggest that the fast-responding control facilities situated within the converter facilities of MH's Dorsey Station improve the thermal capability of its interconnected AC meshed network by some 40%.

regional AC meshed networks, and thus could mitigate the need for investment in various forms of series compensation or larger thermal capability within AC systems.

SUMMARY

Hydro's AC Network: For the AC network currently in place, the study suggests that Hydro's transmission operating expenses lie below the typical cost experience of AC systems operated by other utilities. For years 2014-2016, Hydro's mean transmission O&M cost level for AC transmission averages $7,377 per mile. Hydro's transmission O&M costs are not too far removed from 2014-2016 sample minimums for the U.S. utilities, $4,741/mile, and well below the sample median of $11,721/mile. Similarly, the 2016 mean and median of transmission O&M costs for the Canadian utilities are $12,961/mile and $11,146/mile respectively, compared to Hydro's cost level of $6,559/mile, also for 2016.

Labrador Transmission Assets: Cost benchmarks for AC facilities including the LTA and Hydro's current AC network are more robust because of available data: electric utilities generally report transmission system-wide O&M costs within the public domain. This richer-reported cost experience is the foundation for the O&M cost estimates for LTA and Hydro's existing AC system. For LTA, the study finds that LTA's operating costs should fall within the range of $4.5 to $7.2 million CAD.

Labrador Island Link: This study finds that the overall O&M costs for Labrador Island Link are likely to reside within the range of $17.4 to $25.5 million CAD, substantially above the cost level of conventional AC facilities of similar capability and length.[13] This large gap in cost level stems directly from the costly converter stations associated with the interconnection of direct current to Hydro's AC transmission grid which constitutes the island system. These cost findings reflect limitations in data availability, as HVDC cost information is generally not broken down by individual facilities in the public domain.

DATA, STUDY DEFINITION

***Data Sources and Limitations*.**

Transmission operating cost data are reported at a summary level and made available within the public domain. In Canada, electric utilities provide quarterly and annual cost reports to the regulatory authorities of the several Canadian provinces. For U.S. utilities, transmission operating cost data are available in annual frequency according to category of equipment (e.g., lines, underground cables, substations). Reported O&M costs cover all facilities and equipment for a defined category; for example, the reported O&M costs for substations of a large utility may cover over 100 stations.[14]

[13] It is only relevant, arguably, to view lines-related costs of HVAC and HVDC systems on a per unit of distance basis insofar as it would not typically be feasible for AC facilities to stretch the route length of many HVDC facilities, including that of Labrador-Island Link. Worldwide, the longest HVDC system currently in place is Brazil's Rio Madeira, a 2,385km-600kV facility.

[14] It is useful to mention that, though operating cost experience is not generally available in the public domain on an individual facility basis, estimates of transmission investment costs can be developed from available public

While HVDC facilities are specialized, reporting entities combine O&M costs of HVDC with the costs of other facilities of similar type. For example, converter facilities and equipment often reside within large substation yards. O&M costs of the HVDC facilities are aggregated within the costs of the substation. In brief, O&M costs of HVDC facilities are two steps removed from reported O&M costs, and are not generally found in the public domain. For the immediate study, the O&M costs of the converter facilities of two HVDC systems are used as the basis to develop plausible cost benchmarks for the converter facilities of Labrador Island Link. O&M costs for one facility are observed (Dorsey Station, Manitoba Hydro); O&M costs of a second facility are based on estimates included within the system design (Thailand-China interconnection).[15]

O&M Costs for Benchmarking AC Networks, Including LTA and Hydro's Transmission System. The analysis of O&M costs for AC networks is focused on the direct operations and maintenance expenses associated with conductors, towers, substations, and related equipment, as recorded by utilities during the 2014-2016 timeframe. The analysis compares Hydro's transmission O&M expenses to the sample of Canadian utilities for 2016, and to the sample U.S. utilities for 2014-2016, with results reported separately for each year. The Study incorporates administrative and general expenses (A&G) attributable to the transmission function, and adjusts the O&M costs of U.S. utilities for the CAD-USD exchange rate, computed as the average of the monthly values for each year, 2014-2016.

Canadian Utility Sample: Transmission O&M cost data for the Canadian utilities are reported on a circuit/km basis, and are obtained from financial reports and submissions by the utilities to provincial regulatory authorities responsible for setting electric utility rates. The categories of cost data reported by Canadian electric utilities are generally uniform across the provinces. Nonetheless, differences in cost definitions are present in this study and can assume several forms including: methodological differences for assignment of A&G costs to functions; definitional boundaries for separating transmission and distribution; attribution of substations situated at generators to transmission or generation; and whether the system control function is viewed exclusively as generation (dispatch, operations planning) or both generation and transmission. In the case of the Canadian utilities, system control activities are incorporated within transmission O&M costs, as reported.

U.S. Utility Sample: For the U.S. utilities, O&M cost data were drawn from the annual reports of electric utilities to the Federal Energy Regulatory Commission (FERC). These reports, referred to as Form 1, provide in-depth data with respect to costs by function, levels of output/sales (MW, MWh), wholesale

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domain data. Investment cost estimates are made available for specific transmission facilities, differentiated for conductor density (e.g., dual or triple bundles), types of towers, conductor sizes, and types of terrain over which lines are installed. Cost estimates are typically reported on an investment cost/mile basis. Our research also found all-in investment cost estimates for HVDC facilities, specified for selected sizes of facilities.

[15] The O&M costs of converter facilities include observed and estimated costs. O&M costs for Manitoba Hydro's Bipole I and II converter facilities are observed. Estimated O&M costs are drawn from operating budgets for the converter stations of the HVDC link between the Electricity Generating Authority of Thailand (EGAT) and Southern China HVDC, which is currently in process of completion. This new facility is part of the integration of the transmission networks of the Association of Southeast Asian Nations (ASEAN).

transactions, and the capability of facilities measured according to MW, MVA, and miles of transmission lines in place,[16] as reported in the annual Form 1 submissions by individual utilities to the Federal Energy Regulatory Commission. For purposes of the Study, transmission O&M costs include the FERC-defined expenditure categories for transmission lines, towers, substations.[17]

The 24 U.S. electric utilities are selected according to load density, measured as:

$$load\ density = {}^{peak\ demand}/_{km\ of\ transmssion\ lines}$$

Speaking generally, the transmission function of electric utilities provides transport services—the transport of electricity from the locations where it is produced to the locations where it is consumed. The quantity of transport services supplied by transmission can be measured in two ways: transport distances measured as kilometers or miles of transmission lines/conductors installed; and peak demand served.

These two service dimensions (line distances, peak loads) largely drive costs. For this reason, it is arguably appropriate to compare O&M costs of utilities with similar load density, as density incorporates both distance and peak load service dimensions.[18] Accordingly, the Study selects U.S. utilities that had transmission load density during 2006-2016 broadly similar to that of Hydro during 2016. Load density for Hydro during 2016 is presented below:

(see following page)

[16] Significant differences between circuit miles and pole miles characterize the transmission networks of selected utilities, with circuit miles the larger. Transmission circuit miles are reported at a detailed level within the Transmission Availability Data System (TADS) maintained by the National Energy Reliability Corporation and, at a summary level, for regions. Circuit-miles—pole mile differences can impact the cost benchmarks. Accordingly, the work underlying the study includes a brief internet search for reported circuit miles, for comparison to the pole mile counterparts reported under the FERC Form 1. For the selected utilities, circuit miles closely conformed to poles miles, with the exception of one entity (Idaho Power). Nonetheless, the study assumes that, for each sample U.S. utility, 20% of the transmission pole sets carry dual transmission circuits.

[17] The relevant FERC transmission accounts include *operation supervision and engineering* (Acct 560), *station expenses* (Acct 562), *overhead lines expenses* (Acct 563), *underground lines expenses* (Acct 564), *maintenance supervision and engineering* (Acct 568), *maintenance of structures* (Acct 569), *maintenance of station equipment* (Acct 570), *maintenance of overhead lines* (Acct 571), and *maintenance of underground lines* (Acct 572). Some Canadian utilities also record O&M expenses according to these cost categories.

[18] Higher load density would appear to obtain lower costs, stated on per unit of distance (kilometers, miles), providing that the cost elasticity of transmission O&M costs with respect to peak loads is lower than the cost elasticity with respect to transport distances.

TRANSMISSION LOAD DENSITY, NEWFOUNDLAND-LABRADOR HYDRO

	km	*Peak Load (MW)*
230 kV*	2,064	1,902
138 kV	1,500	
66 kV	673	
Labrador Island Link	1,100	
TL 267	186	
LTA (TL 3101/3102)	500	
Total, km	6,024	
Total km w/o LIL, LTA, TL267	4,238	*kW/Mile*
		0.6214
Total, Miles	3,743	
Total miles w/o LIL, LTA, TL267	2,633	
NL Hydro, Peak Load/Mile	0.51	
Selection Range, US Utilities		
Low	0.38	
High	0.64	

* includes the 230kV circuits between Churchill Falls and Labrador West

As shown, transmission density of 0.51 for Hydro gives a plausible selection range of 0.38 – 0.64. The load densities of the selected 24 U.S. utilities are somewhat higher during 2016, ranging from 0.49 – 0.97.[19]

The O&M costs of the U.S. electricity utility sample is the basis for the O&M cost estimates for Labrador Transmission Assets, as mentioned. For the sample utilities, the reported costs for FERC lines facilities, determined on a per-mile basis, serve as the foundation for the Lines-related cost estimates for LTA. The lower-upper bound range is based on the expected value (means) and statistical distribution of the estimates: *lower bound = EV – 0.25*standard deviation of the estimate; upper bound = EV + 0.15 *standard deviation of the estimate*. For Stations Equipment, the O&M cost estimates are also drawn from the U.S. sample, as measured on a per MW of peak demand basis. O&M cost estimates for Station Equipment incorporate lower and upper bound fixed cost shares of 0.20 and 0.40, respectively, as well as low and high cost adjustments.

The transmission O&M cost estimates reported so far compare Hydro's cost levels to the Canadian and U.S. samples, where O&M costs for Lines and Stations are combined in the O&M cost metric (cost/mile).

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[19] Econometric methods including fixed effects models applied to pooled time series-cross sectional data would likely provide further insight into the major explanatory factors that determine O&M cost levels. *A priori*, we anticipate that contributing factors including terrain and accessibility, age of facilities, types of towers, and the share of underground facilities contribute to the O&M cost levels.

In addition, it is useful to unbundle these overall results into separate Lines and Stations cost benchmarks, reported on a $/mile and $/MW basis, as follows.

LINES-RELATED COST BENCHMARKS

2016 *TRANSMISSION LINES* O&M COST per FACILITY MILE (CAD)						
Comparable U.S. Electric Utilties*						
	Average			*Variation*		
Year	Mean	Distance-Weighted	Median	*S.D.*	*Min*	*Max*
2016	$10,191	$8,940	$7,934	$7,755	$2,064	$36,156
Newfoundland Labrador Hydro						
Year	Total FOM Cost including A&G (000's)			FOM per Facility Mile		
2016	$9,752,293			$3,704		

* The U.S. sample consists of 24 utilities.

STATION-RELATED O&M COST BENCHMARKS

2016 *TRANSMISSION TERMINALS* O&M COST per MW (CAD)						
Comparable U.S. Electric Utilties*						
	Average			*Variation*		
Year	Mean	Peak Demand-Weighted	Median	*S.D.*	*Min*	*Max*
2016	$10,281	$7,267	$6,981	$8,070	$1,397	$38,199
Newfoundland Labrador Hydro						
Year	Total FOM Cost including A&G (000's)			FOM per Facility Mile		
2016	$7,518,356			$3,953		

* The U.S. sample consists of 24 utilities.

The above results confirm the overall conclusion reached by the study: Hydro's O&M cost levels are highly favorable compared other electric utilities.

O&M Costs for Benchmarking Operating Costs of Labrador Island Link (HVDC).

Data Availability and Cost Decomposition: Accuracy and comparability are core features of viable benchmark studies. For transmission, reliable O&M cost comparisons can be obtained in two ways: observed costs of comparably situated transmission service providers; or a well-founded basis to decompose summary level costs, as reported, into the constituent cost components. As mentioned above, O&M costs specific to HVDC facilities are not generally observable within the public domain. However, data non-reporting does not present a serious issue for Lines (conductors, towers, and related equipment), as O&M costs of DC and AC route facilities are highly similar, as described below:

> "…items of equipment associated with HVDC systems are the same or siSSmilar to those located on the AC network, including high voltage transformers, cables, capacitors, reactors etc."[20]

Further, discussions with contacts and our general experience lead us to infer that the Lines facilities of HVDC systems may imply lower O&M costs than AC systems insofar as the quantities of DC equipment are typically less than AC facilities of similar capacity. DC facilities may utilize less conductor and have smaller towers, and the route of DC Lines may also have a smaller footprint. Hence, Lines-related costs of DC and AC facilities are, most likely, nearly equivalent. For this reason, the Study draws on observed O&M costs of Lines for the sample of U.S. utilities,[21] as a proxy for the lines associated with HVDC.

Converter facilities/substations are a different story, as O&M data for converter facilities are not generally available in the public domain. Yet, O&M costs for converter facilities are a major share of total O&M for HVDC. Ideally, O&M costs of individual substations should be compared according to equivalent levels of capability (i.e., MVA transformer capacity), or the specification for facility equipment and componentry.[22,23] Converter facilities vary widely in design scheme, functionality, equipment, and the installed capability to manage power flows (MW) including reactive power. The underlying cost experience is further complicated by the fact that electric utilities maintain converter stations differently, whether via remote oversight, a dedicated staff, or 24/7 personnel. Finally, projects face varying operating standards and reliability requirements. Accordingly, the study utilizes the O&M costs, observed and estimated, for two HVDC systems.

<u>HVDC Systems, and Converter Equipment</u>: Under selected conditions and applications, HVDC transmission can realize concrete cost advantages over HVAC transmission. The foremost condition favoring HVDC is extended transport distances, especially those exceeding 1,000 km.[24] First, with 30%-50% lower line losses, HVDC lines become more economical than HVAC facilities the longer the transport distances.

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[20] *Section 5.3, Operation and Maintenance Requirements*, <u>Grid West Report, HVDC Technology Review</u>, by PSC Specialist Consultants to the Electricity Industry, page 78, December 17, 2014.

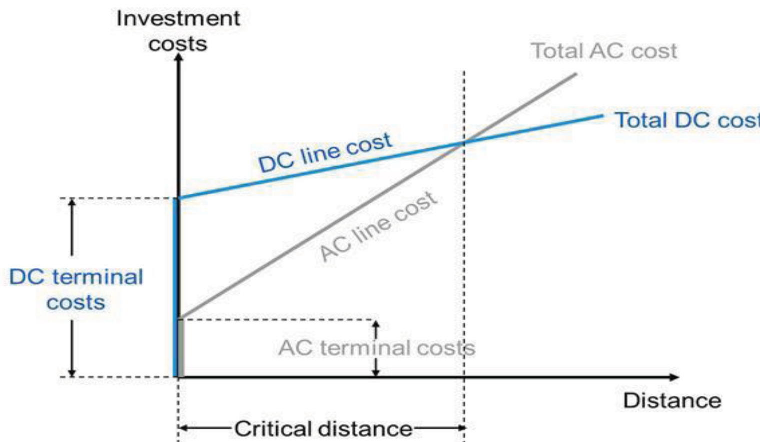
[21] The transmission O&M costs for the sample of U.S. utilities are reported separately according to the main categories of transmission network facilities including system operations-related costs, Lines, underground facilities, and terminals/substations. The Study would prefer to incorporate transmission O&M costs for Lines, for the sample of Canadian utilities. However, cost data for the Canadian sample are not reported in a sufficiently disaggregated form.

[22] http://www.elp.com/articles/print/volume-93/issue-5/sections/t-d-operations/benchmarking-in-action-comparing-the-costs-of-hvdc.html

[23] "There are only three vendors supplying converter stations. Price is heavily driven by the competitive pressure on the companies to procure projects at that specific time. Therefore, the same project procured in a different period might be more or less competitively bid. In addition, virtually all HVDC converter stations are procured through turn-key contracts with strict confidentiality clauses. This inhibits the capability to break station costs down into their constituent components hindering analysis of cost drivers." *Ibid*.

[24] Other conditions favoring HVDC include the span of large bodies of water with undersea cables and system control to manage reliability.

Second, capital investment and installation costs in conductors, towers, and related infrastructure also favor HVDC. An HVDC facility package consists of two converter stations – one rectifier facility (AC to DC) and one inverter facility (DC to AC – connected by either overhead lines or undersea DC cables. A bipolar HVDC facility uses only two insulated sets of conductors rather than three, the case of AC facilities.[25] This results in narrower rights of way and smaller transmission towers, which translates into lower construction and maintenance costs.



Source: Discussion provided by ABB Group.

These cost-saving attributes of HVDC transmission only provide economical electricity transmission if they outweigh charges on investment in converter stations and other project parameters including ongoing O&M costs.

Understanding the costs of DC converter stations requires a brief discussion of the major components therein. Converter station equipment can include thyristor valves, voltage source converters (VSC), transformers, AC filters and capacitor banks, and DC filters to manage harmonics. This equipment play a role in converting power from AC to DC and vice versa. Depending on configuration, the equipment package of converter stations can provide fast-responding control of operating parameters of meshed AC networks, thus improving reliability. Improved system reliability is manifested in important ways, include major increases in flow capability within the meshed AC networks interconnected with HVDC facilities.[26] Voltage source converters, as opposed to line commutated converters (LCCs), provide for more elaborate and faster control of the station's valves (switch gear). Unlike LCCs, VSCs can control real power flow as well as reactive power (the voltage level) and provide the means for the black-start of AC systems.[27] This

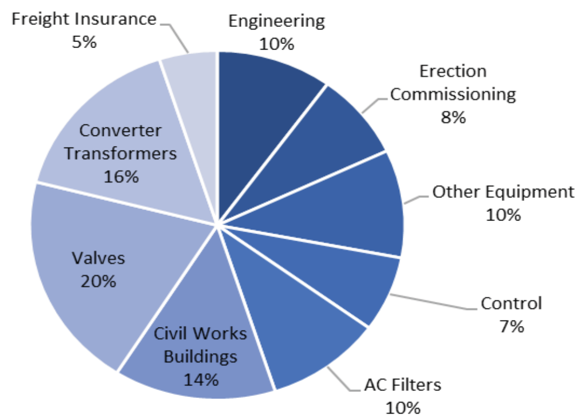
[25] http://large.stanford.edu/courses/2010/ph240/hamerly1/docs/energyweek00.pdf

[26] Testimony of Manitoba Hydro panel on transmission cost allocation during the second day of the Manitoba Hydro Cost of Service Review proceedings, before the Public Utility Board (September 15, 2016).

[27] http://www.e-cigre.org/publication/388-impacts-of-hvdc-lines-on-the-economics-of-hvdc-projects.

has led to a reduction in losses from 3% to 1.7% for the average converter station. For this reason, VSCs have begun proliferating at HVDC converter stations worldwide, with capacities up to 1,200 MW.[28]

Converter station can utilize varying technologies – e.g., VSC vs LCC converters – and provide varying functionality. Maintenance practices and protocols vary accordingly. Viewed generally, the "High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper" cited above breaks down the average cost of converter station equipment, along with all other converter station costs in the following way.



Source: High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper

<u>Methodology Underlying HVDC O&M Cost Estimates, Labrador-Island Link</u>: O&M cost estimates include high and low scenarios, differentiated for cost factors. Lines-related cost estimates are developed on a \$/mile (\$/km) basis, whereas O&M cost estimates are developed on a \$/MW basis.

As mentioned, O&M costs for HVDC facilities are estimated separately for Lines facilities and converter facilities, where cost estimates for Lines is based on the Lines-related O&M cost experience of the sample of 24 U.S. electric utilities. Essentially, the Lines-related O&M cost per mile for the U.S. utilities for 2016 is multiplied by the route distance for the Labrador-Island Link (1,100 km, 684 miles).

The O&M cost estimates for converter facilities are based on 1) Manitoba Hydro's observed costs for the Bipole I and II converter facilities at Dorsey Station (3,800 MW), and 2) cost estimates for the EGAT-Laos-China facility (3,000 MW). Based on the annual O&M costs for these two HVDC systems, low and high scenarios of O&M costs of converter facilities for LIL are developed. The high-low range differentiates O&M costs for the fixed cost share of the total O&M costs and, for Manitoba Hydro, takes account of the costs associated with the rectifier conversion facilities at the Radisson and Henday converter stations.

[28] A major implementation of VSC technology is the Cross Sound Cable Project from New Haven, CT to Shoreham, NY, completed in 2002 by TransEnergie US (TEUS). TEUS cited a number of reasons for choosing VSC-based converters, including the capability to remotely control and monitor the converter system, as well as the advantages enumerated above. Cross Sound Cable was the first use of second generation VSCs for transmission systems, and did encounter some issues as a result of consequent increases in power transfer capability. The Project worked closely with VSC manufacturers to resolve the issues.

Though the functionality of the converter facilities of these two HVDC systems is likely to vary, and perhaps vary dramatically, annual O&M costs appear to be similar in magnitude, stated on a $/MW basis.

The cost estimates for Lines and converter facilities, and the various factors used to determine the low-high range are shown below:

FACTORS FOR DETERMINING RANGE FOR O&M COST ESTIMATES, LINES AND CONVERTER FACILITIES, LABRADOR ISLAND LINK		
Factors for Lines	Low	High
AC-DC O&M cost adjustment	-0.03	-0.07
Standard deviation, O&M costs	-0.25	0.25
Factors for Converter Facilities	Low	High
Share of total costs which are fixed	0.2	0.4
Costs of rectifiers, as share of inversion*	0.5	0.8

* for Manitoba Hydro's Radisson and Henday stations, with reference to Dorsey

The factors for Lines-related costs are described as follows:

AC-DC O&M cost adjustment: O&M costs for Lines are drawn from the U.S. sample of AC networks. Lines-related costs of HVDC are expected to be somewhat less than for HVAC systems. Hence, the low and high cost range adjusts the observed U.S. O&M Lines-related costs downward by 3% and 7%, respectively.

Standard deviation, O&M costs: The median of the U.S. transmission O&M costs is adjusted downward (upward) by -0.25 and +0.25 standard deviations to obtain the low (high) O&M cost estimate, for Lines-related costs.

The factors for Converter Facility costs are described as follows:

Share of total costs which are fixed: O&M cost estimates for converter facilities are, by assumption, assumed to be a function of facility size measured according to flow capability (MW), holding certain parameters (design scheme, functionality, and technology) unchanged. However, a share of converter facility O&M costs is assumed to be constant, and unrelated to flow capability. The 0.2 and 0.4 factors for the low- and high-cost scenarios are the share of O&M costs of converter facilities assumed to be fixed.

Costs of rectifiers, as a share of inversion: The observed O&M costs for Manitoba Hydro's HVDC facilities (Bipoles I and II) are for the inverter facilities at Dorsey Station. Thus, these observed costs for inversion need to be adjusted upward to reflect the conversion cost at the "other end" of MH's HVDC facilities – Radisson and Henday stations. The adjustment factors 0.5 and 0.8 increase the observed O&M costs at Dorsey, which cover the function of inversion, by 50% and 80%, respectively, to obtain total O&M cost estimates for the converter stations of MH's HVDC systems, Bipoles I and II.

In view of data limitations and the underlying cost variation across HVDC systems, it is clear that considerable uncertainty is inherent in O&M cost estimates, particularly for converter facilities. As a consequence, the range factors, applied to the available O&M cost estimates (Manitoba Hydro, Electricity Generating Authority of Thailand "EGAT" and Southern China HVDC) are based on our general experience in applied cost analytics within electricity services. The factors are qualitatively determined and, except for the standard deviation of O&M cost estimates for the U.S. AC networks, are without empirical foundation.

In short, the range for O&M cost estimates is fairly broad. Further investigation of the O&M costs of converter stations would likely cause the range factors, as used in the immediate study, to narrow.