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Electricity Grid Resilience Adaptation Framework - Proposed

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SUMMARY

This paper outlines Hydro One's (Canadian electricity utility) electricity grid resilience adaptation framework with focus on extreme natural hazards. Since the Inter-governmental Panel on Climate Change (IPCC) under certain circumstances expects the inevitability of Climate Change (CC), utilities need to consider reducing/ managing consequences of extreme natural events attributed to CC.

This paper is the result of the dilemma: can a credible grid resilience/ adaptation economic evaluation be crafted to concurrently support utility needs; regulatory rate case filings; and financial market requirements set by Task Force on Climate – Related Financial Disclosures (TCFD) from the Financial Stability Board (FSB), that promotes international financial stability, via coordination with national financial authorities and international standard-setting bodies.

Many climate change evaluation frameworks involve qualitative evaluations for broad policies or broad government initiatives, or attempt to quantify the impact of qualitative factors, such as low/ medium/ high risk levels. Other frameworks consider conventional risk management methods, when climate change resilience and adaptation requires Extreme Value Analyses (EVA). This paper's framework leverages these quantitative frameworks, and considers incremental (Δ) economic evaluations including incremental Cost Effectiveness Analysis (CEA), and Cost Benefit Analysis (CBA) related to extreme incremental resilience changes (e.g. structure reinforcement, process change) for parts of the electricity sector's physical infrastructure. The physical resilience and adaptation options factor in extreme event driven grid analysis for prudent grid security planning and grid operational contingency plans, beyond conventional grid planning principles.

In considering "resilience" economic evaluations, there is the profound observation that "resilience benefits" may actually never materialize due to the infrequent occurrence of extreme natural hazards. Simply said, the benefits from resilience capital investments are uncertain. In some cases, resilience investment comes at a small incremental cost for already proposed capital investment. The Province of Ontario "decarbonized" the electricity sector by shutting down large centralized coal-fuelled electricity generation, and encouraged installation of distributed renewable (solar, wind) generation. This changed the "grid architecture" which needs a more robust transmission and distribution grid.

KEYWORDS
Grid resilience, climate change, extreme value, adaptation, CEA/CBA economic analyses.

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1.0 INTRODUCTION

The electricity grid is critical infrastructure and is interlinked with other infrastructure facilities, such as water, fuel, telecom and pipelines. The electricity grid resilience is vital to life and economy. Based on the Insurance Bureau of Canada, there are increased claims from extreme weather events including ice/wind storms, flooding, drought, tornadoes, thunderstorms, fog, extreme heat and cold. Extreme weather refers to localized short term atmospheric conditions, while climate change refers to regional atmospheric conditions over a long time period.

This paper is the result of the dilemma: can a credible grid resilience/adaptation framework be crafted to concurrently support utility needs; regulatory rate case filings; and FSB and TCFD financial market requirements.

IPCC reports correlate greenhouse gas (GHG) emissions, (e.g. carbon dioxide (CO2), methane, SF6) and warming global climate. CC is linked to more frequent and intense extreme weather with destructive impacts to property, human, animal, and nature losses. Electricity grids are also victims of these events. Scientific studies also indicate that extreme weather events such as heat waves and large storms are likely to become more frequent or more intense with CC. Hydro One as owner and operator of electricity grid infrastructure is not immune from the global effects of CC and natural hazards which affects the grid. The resilient adaptation of CC requires use of extreme value analyses (EVA). The paper proposes a quantitative framework that leverages extreme value incremental (Δ) economic evaluations including incremental cost effectiveness analysis (CEA) , and cost benefit analysis (CBA) to evaluate the grid physical infrastructure for resilience, with considerations of extreme weather events. These physical resilience/ adaptation options factor in extreme weather and environmental events and associated investments needed, to provide supply security to customers; further factoring in grid security planning and grid operational plans, consistent with lifecycle principles. This paper excludes human-caused hazards, cyber security; physical security, and bio-hazards.

2.0 GREENHOUSE GAS EMISSIONS – ONTARIO & HYDRO ONE

Ontario's electricity sector contributes 3% of GHG emissions, out of a total of 159 megatonnes (MT annually) of CO2e (equivalent) {S1}. Ontario's GHG declined 12% from 1990, after Ontario's 2014 coal-fired generation stations were shutdown, that contributed to 34 Mt GHG reductions. Ontario's GHG sources are: transportation 35%; heavy industries 24%; buildings (residential/commercial) 22%; agriculture & waste 10%; oil/gas 6%; and electricity 3%. [S1: Canadian Energy Regulator, 2017, internet, July 2021].

Hydro One's Transmission & Distribution (T&D) grid operations GHG emissions are 0.118 MT (2018), or 2.3 % of Ontario's electricity sector GHG, or 0.07% of Ontario total annual GHG emissions. Hydro One T&D GHG contributors are vehicle fleet operations 50%; SF6 circuit breakers fugitive emissions 45%; and energy for heating/cooling/lighting 5%. This excludes 0.05 MT/year for remote communities' diesel generation which is expected to be significantly reduced with the First Nations-private sector initiative for planned grid connection to these communities.

3.0 CLIMATE CHANGE RESPONSE – MITIGATION & ADAPTATION

A 2012 IPCC report {S2} identifies two key responses to CC risks: [S2: IPCC 2012. Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation].

[a] Climate Change Mitigation (CCM) – to stabilize or reduce GHG to slow or stall CC.

[b] Climate Change Adaptation (CCA) – recognizes CC is inevitable, & manage consequences of CC.

CC has consequences for physical, social and economic systems. Any adaptation changes to practices, processes, or structures may become necessary to reduce current and future impacts of extreme natural events. As extreme events become more frequent and severe, they may threaten to exceed a "coping range" and even create a cascading failure effect. Adjustments made in a single area may be insufficient to derive benefit. Integrated investments tied to other sectors, e.g. water, health, transportation, telecom, sewage, etc. may be needed to derive societal benefits and maintain safety.

3.1 Climate Change Mitigation – Key Past Actions

Ontario Government policies required Ontario's electricity sector to reduce GHG via:

[i] single largest North American GHG reduction with shutdown of 7,560 MW of coal fuelled electric stations generation (~25 % of Ontario's capacity) by 2014, and GHG reduction by 34 Mt/year;

[ii] one of the largest Provincial/State renewable generation installations with 4,964 MW (transmission) and 2,756 MW (distribution) (total wind and solar) generation connected to Ontario's T&D grid from 2009 to 2020. The improved air quality through coal-fired generation shutdown and clean generation replacements was thought to reduce health care costs for Ontarians.

3.2 Climate Change Mitigation – Support More GHG Cuts

Hydro One's core business is "transport of electricity" (not generation) with low GHG emissions, and continues to support all Ontario industry sectors in GHG reductions, recognizing the interconnectedness of nature and life systems. This support includes:

[a-1] Electric Vehicles - Ivy Charging Network is an Ontario Power Generation (OPG)-Hydro One joint initiative for a new electric vehicle (EV) fast-charger network that is planned to be Ontario's largest and most connected with 160 Level 3 fast-chargers at 73 locations planned by end of 2021;

[a-2] Mass Transit (existing and new) systems are being connected to the grid to support transition away from fossil fuelled systems;

[a-3] Conservation Demand Management (CDM) work administered by Ontario's Independent Electric System Operation (IESO) provincially to cut 440 MW of peak demand and 2.7 TW-hour of electricity consumption, with a budget of $692 M in 2021-2014 period;

[a-4] Interconnection enhancements, grid-connected & distributed-connected generation, (including renewables & Energy Storage);

[a-5] Wataynikaneyap Power LP (24 First Nations partnership) to build transmission lines to displace 20 MW of diesel generation in 17 communities, planned by 2023 and C$1.9B cost.

4.0 ADAPTATION/RESILIENCE DEFINITIONS & KEY TECHNICAL INFORMATION

4.1 Resilience – Definitions in the Electricity Sector

One of electricity sector's common goals is to address the impact of extreme events and maintain the system resilience. Presently, there is no consensus on a definition for resilience. For North American Transmission Forum (NATF), resilience (adapted from 2018 NATF Resiliency Summit) is the ability of the system and its components (both the equipment and human components) to minimize damage and improve recovery from non-routine disruptions, including high impact, low frequency (HILF) events in a reasonable amount of time. For North American Electric Reliability Corporation (NERC), resilience is an aspect of reliable operating of the bulk power system; and NERC Reliability Issues Steering Committee (RISC) provides following definitions:

o Robustness – the ability to absorb shocks and continue operating;

o Resourcefulness – the ability to detect and manage a crisis as it unfolds;

o Rapid Recovery – the ability to get services back as quickly as possible in a coordinated and controlled manner and taking into consideration the extent of the damage; and

o Adaptability – the ability to incorporate lessons learned from past events to improve resilience.

Figure 4.1-1 is a model for reliable/resilient operation of a bulk power system proposed by National Infrastructure Advisory Council (NIAC) and NERC RISC.

4.2 Reliability & Resilience – Simpler Words

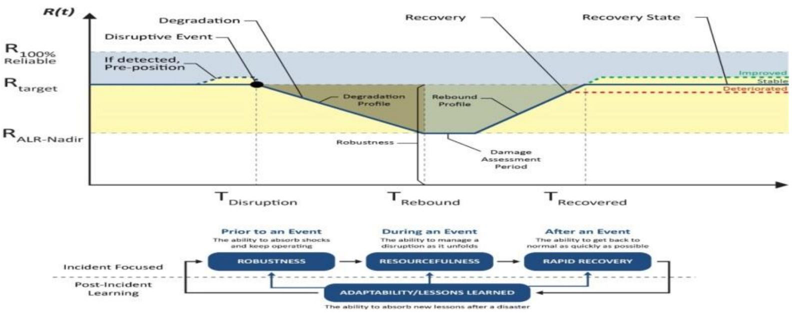
The following provides simpler explanations for key terms used in this document:

Reliability: Keeping the Lights on Every Day {S3}; Reliability is partly characterized by grid disruptions with high number of occurrences (high probability) and low impact (HPLI). [S3: PJM, 2018, PJM's Viewpoint - Reliability and Resilience. Working Toward a Common Goal]

Resilience: Enduring Extremes {s3}; Resilience is partly characterized by grid disruptions with low number of occurrences (low probability) and high impact (LPHI).

Reliability & Resilience could be considered "Co-joined and Dis-similar Twins", noting the grid system is planned, designed, built and operated to ensure both factors are concurrently achieved.

Figure 4.1-1: NIAC/NERC-RISC's Model for Reliable/Resilient Operation of Bulk Power System



[Note: Per NERC R(t) provides a measure of system performance or resilience, to achieve ALR – adequate level of reliability, which requires multi-level effort].

4.3 Resilience In Electricity Sector Practiced For 100+ Years

Electric utilities plan, engineer, built, operate and maintain electricity systems for 100+ years, to ensure safe, reliable and low cost electricity delivery to customers. Resilience is embedded in this lifecycle work, noting electricity's "unforgiving" nature that requires fast controls for real-time load-generation balance. Table 4.3-1lists some key embedded resilience factors.

Table 4.3-1: Key Grid Embedded Resilience Factors

Function/ Category	Grid Embedded Resilience)
Industry Codes & Requirements	◇ Electricity industry planning & operating codes & requirements (NPCC/ NERC/ IESO) for interconnected grids; system contingency analyses; and OGCC grid functions;
Grid Planning & Design; and Engineering	◇ A meshed grid network with consideration of the impact of N-1, N-2, and higher order contingencies, and mitigation plans as needed; ◇ Grid interconnections with abutting utilities for mutual grid support; ◇ Load supply dual-supply concept stations; support; ◇ Critical transmission grid lines with separate Right-of-Ways (RoWs) to prevent co-incident/ common-mode failures; ◇ Adequate spacing of grid lines on common RoWs; ◇ Transmission stations switching flexibility for fast restoration; ◇ Direct telecom pathways (versus "hubs") to ensure OGCC's visibility for status or major equipment or system; ◇ Local standards of major equipment for Canadian weather conditions, including cold/hot/snow/wind/ice accretion/pollution; ◇ Selective equipment enclosures with appropriate HVAC, e.g. Protection & Control (P&C); ◇ Grid stations and lines engineering and builds factors in usual and extreme conditions consistent with industry technical standards including meteorological; climatological; hydrological; geophysical/seismic; ◇ Flood management for specific stations, with water pumps, and back up pumps, with diverse energy sources; and under certain conditions have standby staff for key station floods; ◇ A robust line structure foundations (evidence- see past tower failures; except V-guyed towers in the north); ◇ Lines are engineered to factor in harsher Canadian winter conditions, including ice load and certain wind speeds; ◇ Adjustment to line design requirements from lessons to actual extreme events, including 1998 ice storm event; ◇ Strategic spares (for long lead time equipment) including major power transformers; circuit breakers; parts for some key tower structures, wood poles; overhead and underground cables; and other grid parts;
Grid Operating Flexibility	◇ Managed load-generation shedding; and rotating load cuts to maintain bulk system reliability; ◇ Grid system re-configuration (via switching(; ◇ Load transferability (via switching) ◇ Major equipment including transformers designed for short-term overloads; ◇ System load reduction via system voltage management (with IESO); ◇ CDM (Conservation Demand Management); ◇ Rapid response "virtual" team for P&C settings if a significant portion of grid is unexpectedly out of service for extended time; ◇ Focused Geomagnetic Induced Currents (GIC) monitoring and operational guidelines related to solar storms to safeguard equipment; ◇ Rigorous vegetation management program to ensure NERC line equipment/vegetation clearances requirements; and specific to Hydro One – following a nearer-term reliability improvement using Optimal Cycle Protocol (OCP) vegetation management program; ◇ Operating response, including unique and now "Standardized" Storm Response (in coordination with IESO, and other industry participants) including incident command centre systems; ◇ Mutual aid agreements- surge staffing and equipment under "emergency" conditions; ◇ Activate back-up control centres as required;
Grid Operating Tools for Resilience (with IESO)	◇ People, including system controllers and support staff; ◇ Technology and Tools, including the Network Management System ◇ Processes and Procedures, including OPSRP (System Restoration), Emergency Management documents, processes/ procedures (e.g. Forward Command Centre/ Incident Command Centre, Emergency Operating Centre; Storm Response; safe posture limits (formerly flashover)..
Grid Response / Simulations, and Non-Utility Sector Coordination	◇ Multi-hazard, multi-day, multi-party gird "simulations" (with IESO, major Ontario electricity participants, and possibly neighboring utilities), to ensure event readiness and practice; ◇ Emergency Coordination with non-utility sectors, including multi-level governments, and US utilities and appropriate regulatory agencies.

4.3 Grid Resilience "Threshold" Metric – Hydro One 2β Method

To distinguish among grid reliability and resilience events, and the absence of an industry accepted resilience metric, Hydro One transmission reliability statistics were examined for the 1993-2020 period. In statistics, variability is measured by standard deviations. Exploratory work on variance is underway and one approach to account for uncontrollable events is the exclusion of major events criteria, referred to as the '2β Method'. Specifically, the exclusion of any event interrupting 10,000 MW-minutes or more of unsupplied energy. This threshold is about 1.95 (log normal; and "rounded to 2") standard deviations above the average. This is an application of EVA. Since the utility sector has only collected grid reliability information for less than 50 years, the statistics sample size for "resilience" events are very small, noting that HI-LP events usually have return periods of 20, 50, 100 or more years, and secure long-time period historical extreme grid events is challenging.

4.4 Information For Resilience Framework – Weather Scenarios & Equipment/ Grid Capability
Applying the resilience framework requires at least four broad pieces of technical information:
[i] Characterization of "stressors" in the form of weather hazards associated with IPCC's four future climate change projections. Local weather history and projections including average change and extreme weather change, and their probabilities, to estimate grid equipment/facilities impacts;
[ii] Characterization of "strength/capability" of grid equipment/facilities, including and not limited to equipment structural, thermal, electrical voltage withstand, or other equipment capabilities;
[iii] Characterization of a "decentralized renewable energy with power-electronic inverters; and managed multi-area operations" for the grid that begs/asks for a utility industry driven roadmap.
[iv] Characterization of known interdependence areas, such as storms and emergency storm-water pumping load; drought and hydro generation loss; load and temperature, temperature and capacity, etc.

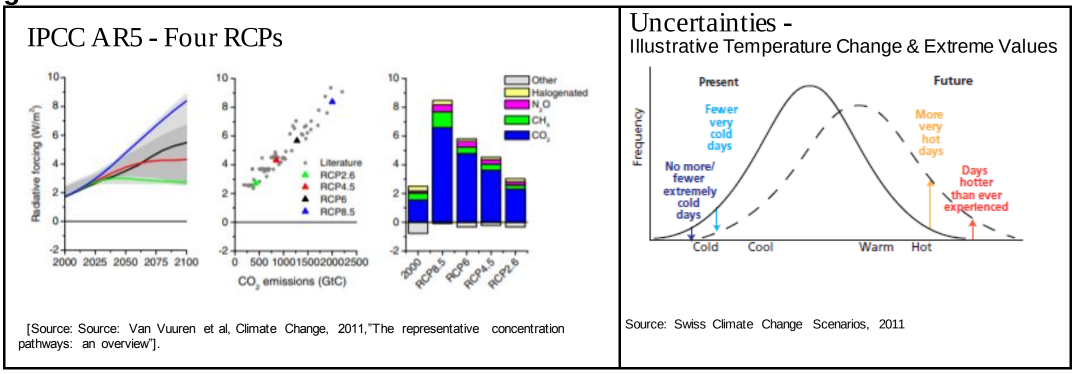
4.4.1 Information To Characterize Weather Hazards & IPCC
IPCC calls for climate change "action" in the IPCC Fifth Assessment Report {S4}. [S4: IPCC, Oct 2014, AR5], which includes four climate change atmospheric concentration (not emissions), defined as Representative Concentration Pathways (RCPs) as in part of Figure 4.4.1-1. (These could be superseded by IPCC AR6 work linked to "The Physical Science Basis" to be issued in 2021). IPCC's RCPs includes:

- RCP2.6 (low emission scenario);
- RCP4.5 and RCP6 (intermediate emission scenario); and
- RCP8.5 (high emission scenario);

RCPs (NRCan, 2019) indicated the change in radiative forcing – the imbalance between solar radiation entering climate system and infrared (longwave) radiation leaving it caused by greenhouse gases, with radiative forcing corresponding to 2.6, 4.5, 6 and 8.5 W/m2 by year 2100.

For grid infrastructure engineering applications, a practical set of guides is needed to address the impact to system and equipment design. There is no specific guidance from IPCC. With more than 40 different global CC models, the different projections of extreme weather lead to further uncertainty. In projecting changes in extreme weather, in one of the US EPA works {S4}. [S4: Katz R (US EPA, Methods for Analyzing Extreme Events Under Climate Change], we should be cautious that the mean value seems to be sufficient to explain the trend in occurrence of extreme minimum temperatures. However, these statistical methods can potentially overestimate the frequency of extreme temperature weather conditions (see Figure 4.4.1-1 – Uncertainties).

Figure 4.4.1-1: IPCC AR5 – Four RCPs & Uncertainties



2019 Canada's Changing Climate Report {S5} [S5: NRCan 2019, CCCR] lists specific extreme and average weather for Ontario, based on IPCC Fifth Assessment Report {S4}. NRCan's provides Ontario specific climate change history and projections including average and extremes (e.g. temperature, precipitation snow, ice and fresh water availability). Other independent projections from the Province of Ontario and academic institutions provide localized area projections. Such data need consistency checks before being utilized by a utility.

The US and Canada utility sector needs to develop guidelines or "Reference Case(s)" to guide the grid planning, designing, engineering, operating, and maintaining to be consistent with IPCC's RCPs, including shift current practices to considering more extreme events, such as 100 year return storms.

4.4.2 Information to Characterize Strength/Capabilities of Grid Equipment/Facilities
The electric utility sector applies technical standards, codes, government regulations, utility practices, and specific utility technical requirements to meet the minimum design/engineering and construction requirements. This is also true for equipment/facilities life-cycle activities including operating, inspection, maintenance, repair, and equipment end-of-life disposal. In context, at least two purposes of these technical requirements are:
[i] ensure the equipment/facility provides intended function under specified operating condition for a specified or estimated time period with normal equipment/facility wear-down; and
[ii] withstand certain defined severe operating conditions and hazards which are usually infrequent. Since electricity is an unforgiving form of energy, there are some technical requirements which necessitates defining equipment/facilities requirements under severe/hazardous conditions. In other cases, only guidance is provided to address such issues, where certain factors such as site specific locations may require specific needs in spite of the utility industry drive to "standardize" equipment. This partly drives the need for local extreme weather data to carryout adequate technical assessments.
The US and Canada utilities and their suppliers need technical guides to apply "Reference Case(s)" of natural hazards for planning grid infrastructure, building & modifying grid equipment and facilities.

4.4.3 Information to Characterize "Decentralized Renewables Energy & Multi-Area Operations"
The Ontario grid "architecture" fundamentally changed by policy to cut CC GHG emissions via:
[i] decommissioning of 7,560 MW of coal fuelled electric stations generation by 2014;
[ii] commissioning 7,720 MW wind and solar generation into Ontario' grid from 2009 to 2020;
[iii] CDM; and
[iv] close-out of large nuclear generation stations in the coming few years.

The Ontario grid is fundamentally changed:
(a) Reduced System-Inertia due to Renewable Energy Sources - The former large coal and nuclear power generator units provided grid with physical inertia to stabilize the grid after electrical disruptions or faults. With "decentralized" renewable sources, Highly Intermittent-Highly Variable (HI-HV) electrical output with power-electronic based inverters (to convert DC to AC power) provide little or no system inertia;
(b) Protection & Control and Telecom (PCT) Capability Reduced - The introduction of inverters from renewable generators in the grid affects the capability of the existing PCT functionality to instantly detect disruptions and safeguard the grid;
(c) System Controls Loss to Distributed Generators - Most Ontario renewables are under the Feed-In-Tariff (FIT) contracts, which have no control provisions at grid level;
(d) Multi-area Micro-grid for inverter-based energy sources, with capabilities for stand-alone and grid-connect operating capabilities, potentially with energy storage technology; and,
(e) Advance-Contingency Planning is Required – provide for higher order system contingencies (N-k, k>=3) for key parts of the grid, and economic restoration provisioning (e.g. plan islanded operations; provide reserve margins, extra system isolation & synchronizing equipment, etc).
The utility sector needs dedicated funding to manage a radically changing grid in order to maintain system reliability and resilience.

5.0 ADAPTATION/ RESILIENCE FRAMEWORK

5.1 Adaptation/Resilience Multi-Discipline Framework for Electric Sector
There are many frameworks for assessing consequence of extreme natural hazards. For the electric power sector (including grid), there is no "end to end" plan, i.e. from IPCC's climate change

projections to economic evaluation of adaptation/resilience actions. Hydro One leveraged the work of {S6} [S6: EPRI, Feb 2016 Electric Power System Resiliency: Challenges & Opportunities], NREL, and Hydro One's own experience, to develop an Adaptation/Resilience Multi-Discipline Framework For Electric Sector. Tables 5.1-1, -2, -3, takes an "engineering" framework approach (with progressively more detail), to enable investment/regulatory quality results to rationalize adaptation/resilience "coping" options. This framework is challenging, noting the large scope of Hydro One's grid facilities; and resilience work in this paper relied on technical judgement of experienced staff.

Table 5.1-1: High-Level Adaptation/ Resilience Framework For Electric Sector

Power System Major Systems/ Facilities	Hazards (Climate Change)	Technical Risk Assessment (Change In Extreme Parameters)	Economics: Risk Reduction & Priorities	Resilience/ Adequacy Of Risk
Apply Life Cycle Approach				

Table 5.1-1 identifies a life cycle approach as a "cross-check" to include key resilience factors. Tables 5.1-2, -3 are self-explanatory.

Table 5.1-2: Intermediate-Level Adaptation/ Resilience Framework For Electric Sector

Power System Major Systems/ Facilities	Hazards (Climate Change)	Technical Risk Assessment (Change In Extreme Parameters)	Economics: Risk Reduction & Priorities	Resilience/ Adequacy Of Risk
◇ Generation ◇ Energy Storage ◇ Grid - Transmission ◇ Grid - Distribution ◇ Loads	◇ Natural Hazards ◇ Technological Hazards ◇ Human Caused Hazards ◇ Other	◇ Technical Risk • Hazard's Localized Extreme Tech Parameter Measures • Technical Vulnerability • Tech Risk Assessment • Tech Risk Reduction / Adaptation Options - Incremental Δ Risk ◇ Numerical Δ Risk (If Rqd.) ◇ Integrated Grid Assessment ◇ Uncertainty/ Sensitivity Analyses	◇ Economic Evaluations NPV:Net Present Value • Economic Δ CEA (Cost Effectiveness Analysis) • Economic Δ CBA (Cost Benefit Analysis) ◇ Priorities	◇ Adequacy of Risk ◇ Coordinate With Other Sectors

Table 5.1-3: Adaptation/ Resilience Framework For Electric Sector

Power System Major Systems/ Facilities	Hazards (Climate Change)	Technical Risk Assessment (Change In Extreme Parameters)	Economics: Risk Reduction & Priorities	Resilience/ Adequacy Of Risk
Generation • Hydroelectric • Nuclear • Coal • Gas/ Oil/ Bio • Renewables Energy Storage Grid - Transmission • Transformer/ Switching Stations • Transmission Lines • Transmission Underground Cables • Protection & Control, Telecom (PCT) Grid - Distribution • Distribution Stations • Distribution Lines • Distribution - Under Surface Cables Loads • Power Electronics • CDM/ BTM	Natural Hazards • Meteorological • Climatological • Hydrological • Geophysical • Solar Storms Technological Hazards • Unintentional Tech Eng Flaws/Failures • Aging Infrastructure (e.g. End of Life) • Grid Architecture Change (Carbonless Fuel & More Power Electronics) Human Caused Hazards • Adverse Intentional: Physical, Cyber, High EMP, Bio Other • Human Error & Accidents • Aging Workforce • Few Industry Corps (Supply Chain) • Intra & Different Industries (e.g. Gas & Electric Generators) • Nationalism/Politics • Pandemics (Worldwide & Long Duration) [More details in Section 5.2 For Grid Resilience]	Technical Risk • Hazard's Localized Extreme Tech Parameter Measures Relevant To Specific Power System (PS) Facility (Exposure/ Hazard Probability). E.g. Hazard Intensities & Freq./ Return Periods). Apply GIS • Technical Vulnerability Specific PS Facility' Tech Capacity "Thresholds" & "Gaps" Where Hazard Could Disrupt/ Damage. E.g. Limited Capacity, Or No Tech Hazard Provisioning • Tech Risk Assessment [i] Scope Of Potential Disruption/ Damage To Specific SP Facility (E.g. Permanent Damage Of Specific Equip, & Temporary Non-Function Of Other Equip). [ii] Estimate Incremental Tech Scope Of Climate Change Disruption/ Damage (vs "Base" Capacity "Threshold") • Tech Risk Reduction / Adaptation Options For Specific PS Facility' Incremental Δ Risk Reduction Options Attributed To CC (Climate Change); Factor A Life Cycle Approach (LCA) Since Non-Hardware option Possibly More Effective Numerical Δ Risk (If Rqd.) • Likelihood (L) • Consequences (C) • Risk (= L * C) • Δ Risk (CC Related) Integrated Grid Assessment • Grid System & Hazard Impact Assessment; Restoration Uncertainty/ Sensitivity Analyses • Level of "Embedded" Uncertainty In Analyses • Methods: Analytical For Normal Distributions; Decision Trees	Economic Evaluations NPV:Net Present Value Economic CEA (Cost Effectiveness Analysis) • Δ Costs For Risk Reduction (CRR) Options • Δ Tech Risk Reduction Δ TRR; (Or Monetized Avoided Facility / Company-Level Disruption/ Damage "Costs"). Potential Risk Reduction • Δ CEA Index = Δ TRR/ Δ CRR; or Δ CEA (NPV) = Δ TRR Benefits - Δ CRR Economic CBA (Cost Benefit Analysis) • Δ Costs For Risk Reduction (CRR) Options • Δ Benefits (including Δ Risk Reduction, & Externalities (e.g. Avoided Societal Factors, Beyond Company-Level "Costs")) Priorities • Prioritize Similar Equipment/ Facilities • Prioritize Different Categories Equipment/ Facilities	Adequacy of Risk • Robustness ("Absorb") • Resourcefulness (Manage Crisis) • Recovery (Rapid Service Return) • Adaptability (Learnings & Enhance) Coordinate With Other Sectors

5.2 Electric Grid & Hazards

For an electric grid Table 5.2-1 provides a more complete list of hazards, including resilience literature overlooked technological hazards. Hydro One has a focused system renewal/ sustainment program to address aging electric grid facilities. As noted earlier, this paper focuses on natural hazards only.

Table 5.2-1: Electric Grid & Hazards

Natural Hazards (Group & Specific)	Technological Hazards	Human Caused Hazards	Additional Hazards

Meteorological, Climatological & Hydrological
• Extreme Cold/ Cold Waves/ Fog & Freezing Rain/ Icing/ Snow/ Hail- storms
• Extreme High Temperatures/ Heat Waves
• Flooding/ Heavy Rains (urban)/ Precipitation/ Storm Surge/ Lake- River- Stream Overflows
• Drought
• Forest /Brush/ Bush Fires
• Lightning Storms
• Tornadoes (usually local)
• High Winds (wide area)
Geophysical
• Earthquakes/ Seismic/Landslide
Solar Storms
• Geomagnetic Disturbances (GMD)
	Unintentional Technical Flaws/Failures/Constraints:
	• Engineering Design Concepts/ Equipment Manufacture/ Materials/ Construction Crafts / Operating/ Maintenance
	Aging Infrastructure - Unexpected Breakdowns
	• System Renewal/ Sustainment For Aging Infrastructure
	Grid Architecture Change
	• Carbon Free Grid: Power Electronic Controlled Renewables Generation; Electrical Loads & Major Grid Voltage Control Equipment (SVCs), Affecting Grid Operational Stability
		Adverse Intentions
		• Physical Security
		• Cyber Security
		• HEMP (High Altitude Electromagnetic Pulse)
		• Bio-weapons (Adverse Intentions)
			• Human Error Including Accidents
			• Aging Workforce (Institutional Knowledge)
			• Dependence
			  ○ Electrical Industry
			  ○ Intra & Different Industries (e.g. Natural Gas and Electric Generators)
			• Major Equipment & Materials Supply Chain
			  ○ Nationalism/Politics
			  ○ Few Major Corporates
			• Compound Hazards (e.g. Rapid Economic Electric Load, & Climatic Cuts In Renewables Output)
			• Pandemics (Worldwide & Long Duration)

5.3 Technical Risk Assessment – Extreme Weather

In Table 5.1-3 the technical risk assessment (column 3, from left) has two objectives for each transmission station and each section of each transmission line in the grid system:

[i] for each weather hazard, assess if the facility's technical capability will be exceeded, with noted probability of occurrences; apply Geo-Info-System (GIS) technology as appropriate;

[ii] separately, assess the grid impact noting the grid characteristics outlined in section 4.4.3 and apply potential advanced power system tools, including grid system restoration.

In some cases, "compound" weather hazards apply (e.g. line structure where wind speed and ice loading are considered concurrently). Noting uncertainties in extreme weather characterization, analytical methods (subject to validation to estimate "compound" variability) should be considered.

5.4 Economic Evaluation of Adaptation/Resilience Work & Priorities

In Table 5.1-3 the economic evaluation (column 4, from left) with Net Present Values (NPV) has two objectives for each transmission station and transmission line, consistent with IPCC guides {s7} [s7: EPRI, Feb 2016 Electric Power System Resiliency: Challenges & Opportunities], Impacts, Adaptation, & Vulnerability

[i] Economic Incremental Cost Effectiveness Analysis (ICEA) for each weather hazard, where effectiveness is the raw technical risk reduction per unit of funds; and,

[ii] Economic Incremental Cost Benefit Analysis (ICBA) for each weather hazard, where the technical risk is monetized based on T&D avoided costs under extreme conditions.

The focus is on incremental risk reduction with adaptation/resilience options for incremental costs. Since resilience involves "extreme" parameters and the category of statistics, EVA should be applied.

Priorities: Economic ICEA would support prioritization of similar equipment/facilities for specific weather hazards. ICBA could be used to prioritize different categories of equipment/facilities.

Difficulty of Rationalizing Resilience Benefit: rationalizing resilience funds are tough, since timeframe for "resilience benefits" are uncertain, and may or may be "used" in a long time horizon;

T&D Avoided Costs: for clarity, T&D avoided costs should not be linked to system operator avoided costs which are generation focused and appropriate for CDM evaluations. Ofgem regulator for UK distribution companies allows for incentives/penalties under Interruptions Incentive Scheme (IIS), and this may be a logical alternative for resilience economic evaluations. Further, Hydro One as a T&D company via regulation is obligated to "pass through" power/energy costs with no markup. Ontario system operator's Hourly Ontario's Electricity Price (HOEP) is not applicable for adaptation/resilience, since HOEP does not recognize the price for critical generators that do not behave based upon hourly market price.

5.5 Resilience Metric and Adequacy of Risk

Table 5.1-3 (column 4, from left) refers to adequacy of risk. Without power sector consensus for resilience definition, there are many views regarding a resilience metric {s8} [s8: Panteli M, IEEE Proceedings, July 2017]. .....The utility sector needs to lead the work on the definition and metric(s) for resilience.

6.0 REMARKS – INDUSTRY 'VALIDATION" PROJECTS

Utilities need to jointly or independently apply, test and "validate" resilience work for small projects (involving part of their grid) based on completed research by industry research & academic organizations, including resilience frameworks, definitions, and metrics; advanced power system tools (e.g. N-k contingencies, inertia-less macro-micro grid operations, sub-grid identification with macro-grid capabilities following major grid disruption); dedicated focus & validation for economic resilience framework, factoring frequent & severe weather with grid architecture changes. Utilities should share their validation result to "standardize" resilience economic evaluation (with EVA).