Achieving electricity grid resiliency

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Executive summary

Increasing frequency in severe weather events and resulting system failures and power disruptions create an important consideration for energy planners and designers to increase energy system resilience. Extreme weather events of the past decade have made us more aware of the impacts that climate change can have over energy systems. Therefore, while it is crucial to investigate and mitigate impacts of energy use on climate change, the changes proposed should also create a more resilient urban environment. A systems approach is required to investigate the issues of resiliency and risk mitigation in face of extreme weather conditions. A resilient energy system is one that can ensure secure balance between energy supply and demand despite internal and external developments/influences such as climate change.

This paper falls within the broader scope of *Building Resilient Cities*, in particular the impacts of climate change on the urban electrical grid infrastructure. We explore the use of technological advancements, innovative policies and infrastructure hardening to improve electrical grid resiliency at a local and regional level (Toronto and Ontario).We explore the meaning of resiliency, differentiate it from the commonly used term of reliability in electrical power systems, determine different metrics used to measure it and provide suggestions to increase technological and human capacity and knowledge of resilience/resiliency. Further, this study aims to fill the gaps that exist today - policies, regulatory, technical, economic assessments and propose measures to address them.

This was done through (a) literature reviews to identify relevant reports on increasing electrical resiliency, (b) discussions with different relevant organizations from the point of view of gathering their thoughts on issues, and (c) our own research and analysis in order to meaningfully amalgamate all the above into useful and practical information. The aim was to assess the magnitude of the problem and explore views on issues and solutions identifying barriers (policy, regulatory, technical, and economic) & remedies to achieve resiliency. The paper also summarizes studies to date on climate change and key historical extreme events for Toronto/GTA with facts and figures. Also identified are current best practices for achieving large city resiliency and suggestions for Toronto and Ontario.

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City of Toronto
Quality Urban Energy Systems of Tomorrow (QUEST)
Toronto Region Conservation Authority (TRCA)
Centre for Resilience of Critical Infrastructure (CRCI)
Canadian Electricity Association
Metrolinx

Throughout this work, there were many meetings and discussions with members of the Environment & Energy Division of the City of Toronto. We would like to recognize their interest and willingness to participate in our project and for this we express our special thanks to them.

Disclaimer: The opinions and suggestions expressed in this paper are those of the individual contributors alone and do not necessarily reflect the views of the IESO or any other organizations noted above (except as specifically noted in the paper).

Objective and Audience

The objective of this White Paper is to make policy setters, regulators, municipalities, energy service providers including utilities and academia aware of current issues, challenges and suggestions in the area of urban development planning and its interface with urban energy planning, more specifically electricity planning, to ensure a seamless integration of the two and to achieve a sustainable future.

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Section 1: Introduction and Objective

Impacts from a changing climate, such as more severe temperatures, changing precipitation patterns, and more frequent flooding, wildfires, and hurricanes, (Natural Resources Canada, 2008), "have exposed critical energy distribution infrastructure to significant risks in recent years. These impacts have led to adverse outcomes leaving millions of Canadian homes and businesses without power, heating or cooling for extended periods of time" (QUEST, 2015). Since the advent of electricity, our lives have become dependent on a steady supply of power, to run our businesses, our transportation and power our very homes we live in. At the same time, unprecedented urbanization has put additional stresses on the urban grid, due to every augmenting demand and concentration. "The electricity grid faces (at least) three looming challenges: its organization, its technical ability to meet 25 year and 50 year electricity needs, and its ability to increase its efficiency without diminishing its reliability and security" (Amin, 2008). People living in high-rises for instance, of which there are ever more in Toronto, are at higher risk in the event of power failure.

The status quo is changing due to the changing of the climate and its impact on power supply. In order to reduce the impact of such events and provide a reliable supply of electricity, these infrastructures need to be made more robust and more flexible and the time it takes to react, respond and recover to such impacts need to be shortened. In other words, it is essential that the power grid becomes more resilient.

The objective of this White Paper

The objective of this White Paper is to analyze the direct and indirect ramifications of the changing weather and how it impacts the resilience of the urban power grid. The main impetus of this research is the reality of climate change and ever more severe and/or frequent weather extremes such as heat waves, ice storms and intense rainfall/flooding. The goal of this study is to connect the dots between weather and outages, reliability and resilience, infrastructure and smart technology. At the same time we are providing suggestions on how LDC, customers, electrical infrastructure planners and operators (EIPO) and the legislator can act instead of react in improving system resilience.

Why electrical grid resilience is so crucial now and in the future

Electricity drives our lives, our economy and our cities. Without it, our very lives would not only be inconvenienced, but could potentially be at risk. A steady generation and displacement of electricity is thus vital to the functioning of our society. While much public attention has been spent on the generation side of the power industry - calling for more sustainable and greener forms of energy - resilience has only recently begun to capture the focus of a wider audience.

Because most of our critical infrastructure such as health, security, transportation, water and water treatment, etc., has become dependent on the steady supply of electricity, it is paramount that the grid operates reliably on a daily basis and is more resilient in case of an unusual event (Bristow, 2015; Bristow and Healy, 2014). Figure 1, illustrated below depicts the power grid risk for different countries of the world.

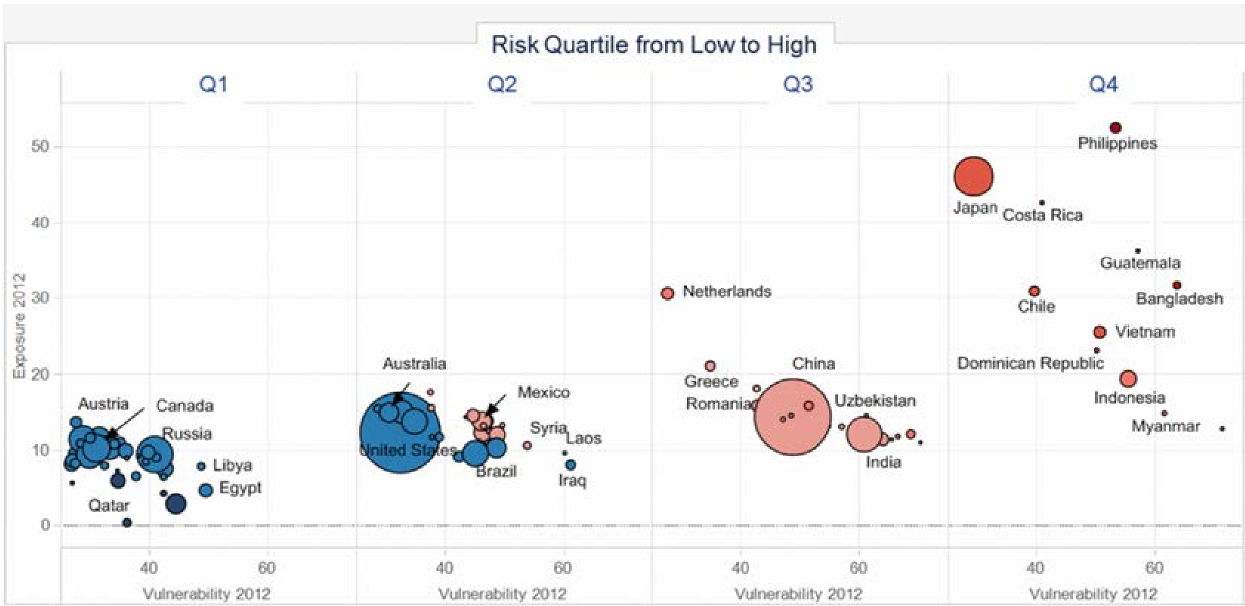

Figure 1 Energy sector vulnerability by country (Source: World Risk Index 2014. United Nations Institute for Environment and Human Security[1])

The increase in severity and frequency of weather events outside the norm is a direct result of the anthropogenic climate change. Climate is responsible for the majority of power interruptions in North America. It is the objective of climate policies to reduce our emissions and thus slow down or even halt the warming of the planet in the long-term. In absence of meeting such goals and quick results, energy system planners and operators around the globe have begun to adapt to the changing environment. The desire to increase the grid's resilience is a result of this adaptation process.

The probability of events that impact system reliability is rather high compared to the probability of events that have negative consequences on grid resilience. That means that smaller interruptions triggered by weather events within the norm or planned outages although occurring more frequently have, in general, relatively low consequences for the consumer and the electrical system. On the other hand, the probability (or frequency) of extreme weather events, such as those outside of the norm, is taken as rather low with consequences that are much severe. However, based on the actual experience of the past decade as well as weather modeling, this is likely to change in the future as events that are negatively impacting a system's resilience are becoming more and more frequent or probable. This problem is illustrated in Figure 2 below.

[1] http://i.unu.edu/media/ehs.unu.edu/news/4070/11895.pdf

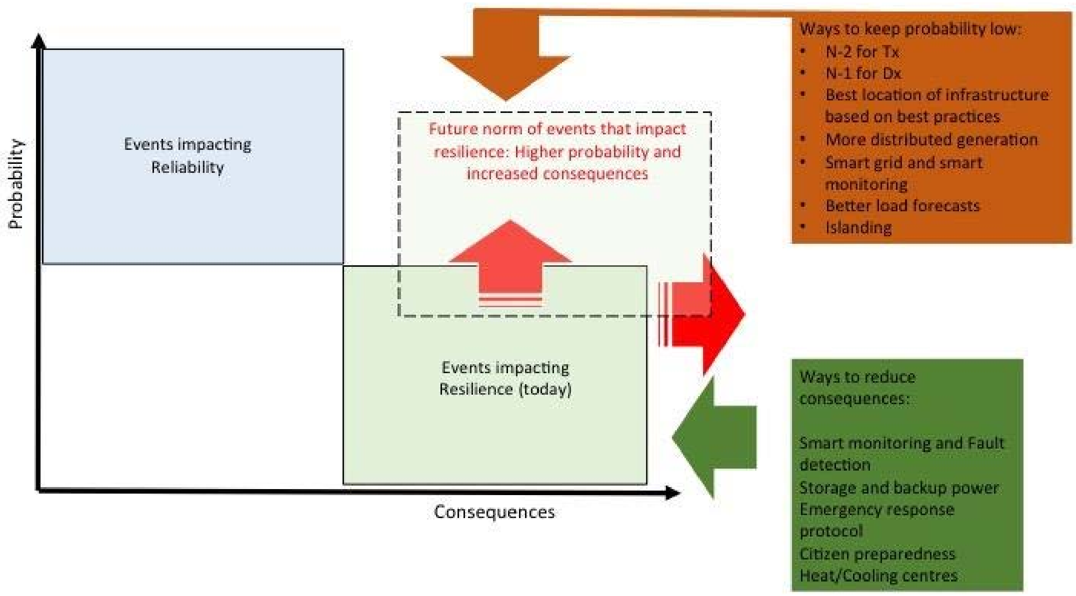

Figure 2 Schematic of the shift towards higher probability (i.e. frequency) and more severe consequences as a result of Climate Change.

By 2019, almost 80% of Toronto's downtown stations will be at capacity (Toronto Hydro, 2015). To maintain power supply reliability, Toronto Hydro has invested close to $3 billion in grid renewal and modernization of infrastructure such as feeders, substations and cables since 2003[2]. As a result, frequency and duration of outages have dropped since 2006. However, this does not mean that there are fewer risks, rather risks have been increasing. There are several elements that have been and are reducing the overall resilience of today's power grid:

- Ageing infrastructure
- Planned interruptions due to rising replacement and maintenance work (triggered by ageing)
- Interference from:
  - Wildfire
  - Vegetation
- Longer Transmission lines (for bringing renewable energy to load centres, longer exposure)
- Expanding Transmission and Distribution network (more assets, longer exposure)
- Population growth and density
- IT Security
- Terrorism

[2] http://www.ontariopetroleuminstitute.com/wp-content/uploads/2014/06/Achieving-Balance-Ontarios-Long-Term-Energy-Plan.pdf

Yet, the single biggest threat to resilience today is...

- Interruption due to severe weather and related events!

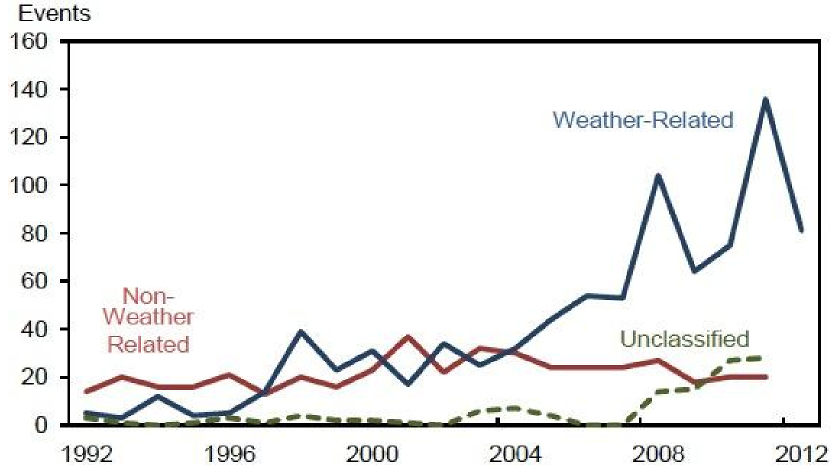

Figure 3 Observed Outages to the Bulk Electric System 1992-2012. (Source: Executive Office of the President, 2013)[3]

How the historical climate extremes impact Ontario's electrical infrastructure

Table 1 depicts the chronology of some of the most severe weather events in recent history in the city of Toronto. The table was prepared by the CUE (CUE, 2015).

[3] http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf

Table 1 Record weather events in Toronto (Source: CUE)

Record Events in Toronto	
2000	Wettest summer in 53 years, with 13% more precipitation than normal
2001	Driest growing season in 34 years; first ever heat alert; 14 nights with temperature above 20°C (normal is 5 nights)
2002	Driest August at Pearson Airport since 1937; warmest summer in 63 years; 5th coldest spring
2003	Rare mid-Spring ice storm where Pearson Airport used a month's supply of glycol de-icer in 24 hours
2004	Year without a summer; May rainfall in Hamilton set an all-time record; all-time record 409 mm of rainfall was set at Trent University in July which was the equivalent to 14 billion litres of water in 5 hours (a one in 200 year event)
2005	Warmest January 17th since 1840; January 22nd blizzard with whiteouts; warmest June ever; number of Toronto days greater than 30°C was 41 (normal 14); August 19th rainstorm washed out part of Finch Avenue
2006	23 tornadoes across Ontario (normal is 14); record year for major storms; record one-day power demand of 27,005MW due to summer heat
2007	Protracted January thaw; 2nd least snow cover ever in Toronto (half the normal amount); snowiest Valentine's Day ever; chunks of ice fell from the CN Tower; 2-3 times the number of hot days in the summer; record latest-in-season string of +30°C days around Thanksgiving
2008	Toronto's 3rd snowiest winter ever; record for highest summer rainfall
2009	3rd rainiest February in 70 years; Hamilton had a 100-year storm; one of the wettest summers on record; tornadoes hit Vaughan-Woodbridge are in late August; an unusually mild and storm-free November in Toronto; first snow-free November at Pearson Airport since 1937
2011	A new all-time July record maximum temperature of 37.9°C was set at Pearson airport
2012	Toronto's earliest official heat wave (June 19-21)
2013	July flood; December ice storm
Adapted from (Toronto, *Resilient City* 4)	

The ice storm of December 2013 marked the most severe storm of its kind in Ontario since the 1998 ice storm that affected eastern Ontario and southern Quebec. The city of Toronto was one of the hardest hit areas during that event. Even though, utility workers prepared for possible downed power lines and warned residents to expect power outages, at the height of the storm, more than 300,000 Toronto hydro customers were without power or heat. According to Abi-Samra et al., (2014) “Hydro One, which serves mostly rural areas of Ontario, reported more than 130,000 power outages at the height of the storm. Thousands of customers remained without power well after Christmas day (p.62). In total the storm negatively affected around 1,000,000 people”.

Hurricane Sandy of October 2012 impacted approximately 65,000 customers in the Toronto Hydro Service Area, whereas the flash flooding in July 2013 left approximately 300,000 customers without power due to damages to underground equipment (Toronto Hydro, 2015). Severe weather events are not limited to ice storms and flooding. In July 2011, Ontario experienced extreme temperatures in the range of 50 degrees C (with humidex). Yet compared to the last serious heat wave in 2006, Ontario’s power grid has seen an increase in supply and decrease in demand, allowing the grid to handle severe heat events better. This is crucial, since Toronto is a summer peaking city. 2006 was the year that saw a record all-time high peak of just over 27,000 MW. In August 2014 the peak demand was 21,363 MW (see IESO). The reason for this decrease in demand can be found in a decline of industry load. At the same time, Toronto is experiencing an unparalleled housing boom without equal in North America. The city is now the fourth largest city by population in North America and a continued leader in high-rise developments, with 157 in existence and a total of 112 under construction. These developments not only put pressure on the grid in terms of power delivery, but also decrease the city’s overall resilience. That is, dwellers in high-rise units are more vulnerable to power outages compared to low-story building residents.

What has been done so far to address severe weather?

The 2010/11 "Making Cities Resilient" campaign was launched and it was built on earlier UN campaigns for safe schools and hospitals, and disaster reduction education. The campaign developed the so-called "Ten essentials for making cities resilient".
Even though Toronto was found to be the most resilient city out of 50 world cities (according to the Grosvenor real estate firm), Toronto still remembers the ice storm of December 2013, the frequent flooding of the Don River, (Corporate Knights, 2015). The Rockefeller Foundation, for example, now supports 100 city-based 'chief resilience officers' as part of its Resilient Cities campaign. But how to measure urban resilience is today's big challenge. If the IESO expects conditions such as extreme temperatures (hot or cold), hurricane, ice storm, forest fires, it may commit additional generators, reject or revoke planned outages, or other actions appropriate for the circumstances.

The Toronto Environment Office and an NGO known as Greater Toronto CivicAction Alliance (CivicAction) are partnering to facilitate climate change adaptation initiatives among and across sectors, and have started with a focus on the electrical sector. The Toronto region faces a variety of weather and climate challenges including heavy rain, flooding, and heat waves. A severe storm in August 2005 exceeded a 100-year record with over 150 mm (6 in.) of rainfall in a three-hour period, resulting in over $647 million in losses. For each of the past three years, insurance companies in Canada have paid out an unprecedented $1 billion to policyholders affected by extreme weather. In November 2011, the Toronto Environment Office and CivicAction launched the WeatherWise Partnership to better protect the region's residents, organizations, infrastructure, and environment from extreme weather. The goal of the WeatherWise Partnership is to identify risks and prioritize areas for action and investment by businesses, communities, organizations and governments as the region faces more extreme weather. The Partnership has over 50 members from all three levels of government and from many sectors such as finance, insurance, communications, real estate, electricity, universities, energy, transportation, and telecommunications. It has identified the electrical sector as its first priority for improving extreme weather resilience in the Toronto region.

Section 2: Electrical Infrastructure (EI) Reliability and Resiliency

How electrical grid resilience is defined and measured

Resilience can be defined in different ways. Some scholars understand grid resilience not as a means to withstand a storm without any damage, but define it as a set of measures that minimize the impact of the resulting damage by enabling electric facilities to continue operating and restore service quickly in the event of power outages (Abi-Samra *et al.*, 2014). On the other hand Ouyang et al. (2014) define resilience as the joint ability of infrastructure systems to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation. Holling (1973) sees resilience as the ability of a system to absorb external stresses, while Woods (2005) add to that elements of foresight, anticipation, and the ability to defend and take measures against the changing environment of risk before accidents occur. Haimes (2009) defines resilience as "the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks" (p.498). According to the Presidential Policy Directive 21 (2013)[4], resilience is the "ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (p.19).

Most definitions have two things in common; (1) resilience differs from business as usual operations and refers to the leading up to, the *event* itself, and the recovery from the *event*; and (2) resilience is a vector due to its dependency on time.

[4] (http://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-securityand-resil).

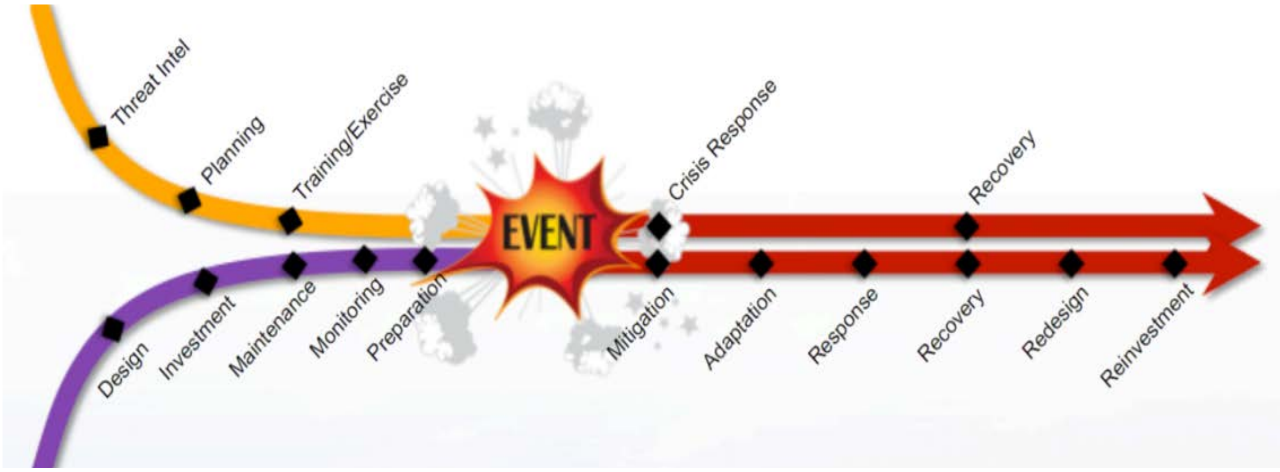

Figure 4 Critical Infrastructure Planning and Operations Timelines: The top-most vector represents operator knowledge and actions. The bottom-most vector represents various aspects of system design and operation. (Source: Sandia Report, 2014)[5]

Due to the multifaceted and interdisciplinary components of resilience, its measures and metrics are equally diverse. Traditionally, improving a grid's resilience encompasses the upgrading and strengthening of power poles, towers, lines and other hardware equipment, as well as trimming trees near power lines. Along with these traditional approaches, today's power grid can also be made more resilient by making it smarter and more flexible in order to prepare for, withstand, adapt to and recover from adverse consequences. The Sandia Report (2014), presented resilience and its multiple components in the following way, depicted in Table 2.

Table 2 Components of resilience (Source: Sandia Report, 2014)[5]

Capacities	Prepare	Withstand	Adapt	Recover
Example Infrastructure Attributes	Advance warning	Robustness	Rerouting	Mutual Aid Agreements
	Prepositioning	Redundancy	Substitution	Situational Awareness
	Stockpiling	Storage	Rationing	Resource Availability
		Separation	Reorganization	

Thus, critical parameters to determine the resiliency of a system are:

- **Robustness**: The ability to absorb shocks and continue operating; (relates predominately to frequency of interruption)
- **Resourcefulness**: The ability to skillfully manage a crisis as it unfolds reducing extent of damage, this is achieved through redundancy; (relates predominantly to duration of interruption)

[5] http://energy.gov/sites/prod/files/2015/02/f20/EnergyResilienceRpt-Sandia-Sep2014.pdf

- **Rapid Recovery:** The ability to get services back as quickly as possible (relates to duration of interruption); and
- **Adaptability**: The ability to incorporate lessons learned from past events to improve resilience. This construct allows universal concepts of resilience to be understood and shared across critical infrastructure sectors and between industry and government. Thus principles of diversity, flexibility, co-ordination are required to increase adaptability.
- **Raised awareness and preparedness**: The ability to convey the message of the perils of climate change for the distribution of electricity through education. As a result of this awareness, consumer behaviour can change (i.e. reduce) and yet the public is prepared and knows how to respond to power interruptions.

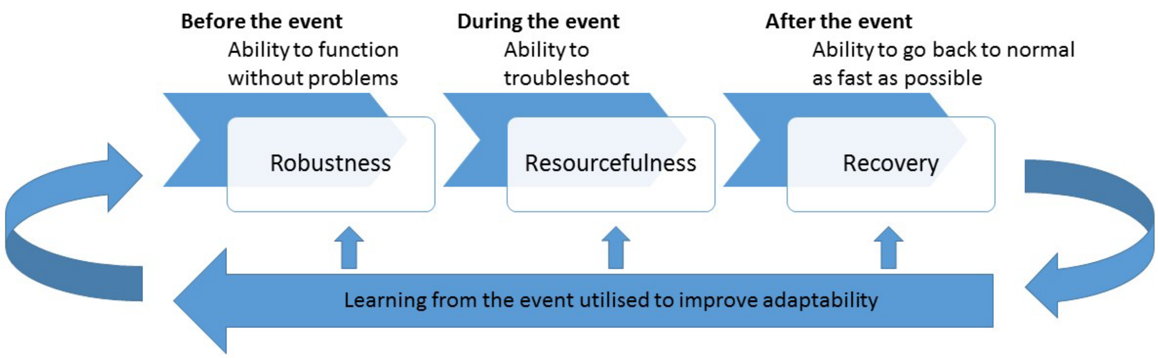

Figure 5 Increasing resilience to adverse events

Some of the earlier work concentrated on environmental resilience coinciding with the emergence of the sustainability movement, which started in the late 1970s, focusing on hazards and man-made catastrophes (Holling, 1973, 1986; Peterson et al., 1998). Parallel to this, the academic community also examined community resilience and the "application of the resilience concept to natural hazards was initially the focal argument in the assessment of natural hazards (Mileti 1999), which suggested that resilience was the ability of a community to recover by means of its own resources" (Cutter, Burton and Emrich, 2010, p.1). At the turn of the millennium, Climate Change became the focal point of the first resilience indicators studies (Adger, 2000; De Bruijn, 2004; McClanahan et al., 2012; Mumby et al., 2013).

In the wake of 9/11, the impetus for resilience studies shifted towards security and critical infrastructure, creating their own benchmarks and indicators (see Cutter, Burton and Emrich, 2010), modeling (see Ouyang , 2014), and control systems (see Capodieci, et al., 2010). Electricity and the grid are part of this critical infrastructure, yet there are no generally accepted indicators for improving resilience.

Acknowledging the interdependence of the electrical grid, so-called composite indicators are increasingly recognized as "useful tools for policy making and public communication because they convey information that may be utilized as performance measures" (Cutter, Burton and Emrich, 2010).

How can resilience or resiliency be measured?

A resilient electricity system, even under extreme weather conditions, is expected to yield:

- Fewer outages and interruptions for all customers (i.e., better reliability measures than otherwise)
- Low(er) societal cost (total cost of interruption incl. commercial, industrial and residential)
- Reduced disruption to critical/priority energy consumers, including medical and emergency services, businesses and industry
- The continued ability of the city to maintain its global competitiveness with increased threat from climate change

Resilience is a vague term to describe; however, clarity needs to be brought in defining resiliency as distinct from reliability. Clear identification of resiliency indicators would be an important step towards increasing resilience of electrical grids. While reliability measures (given later in this report) are used to provide an indication of electrical grid performance under the normal range of weather conditions (which would constitute high probability low impact/consequence events), one can also use them to measure electrical grid performance during extreme weather conditions (which would constitute low probability high impact/consequence events). That said, since the extent and severity of impact on the electrical grid and customers can be of a far greater magnitude in the latter case, it seems prudent to introduce other measures that would more accurately provide an indication on:

A. The extent of impact,

B. Robustness and flexibility of the electrical grid in maintaining supply to all its customers and its critical customers during the extreme weather event, and

C. Effectiveness of the utility in restoring electrical supply to its critical and other customers during and after the extreme weather event.

Based on our review of papers and documents in the area of “resilient grid” coupled with our own experience in the electrical utility sector, we suggest that consideration be given to the following specific measures/indicators for electrical grid resilience.

1. Percentage split between overhead and underground systems of the utility infrastructure
2. Percentage of the overhead system damaged disrupting supply to customers at the peak of the storm
3. Percentage of the underground system damaged disrupting supply to customers at the peak of the storm
4. Percentage of customers without power and the outage duration
    a. Effectiveness and speed of restoration effort profile, e.g., 50% of customers restored in X_1 hours, additional 30% restored in Y_1 hours, the last 20% restored in Z_1 hours
    b. Average restoration time per overhead serviced customer

c. Average restoration time per underground serviced customer
d. Effectiveness and speed of restoration effort profile for multi-unit residential buildings - same as (a) but for multi-unit residential buildings

5. Percentage of critical facilities (such as control centers, hospitals, emergency shelters, old age homes) without power and the outage duration
   a. Effectiveness and speed of restoration effort profile, e.g., 50% of facilities restored in X_2 hours, additional 30% restored in Y_2 hours, the last 20% restored in Z_2 hours
   b. Average restoration time per overhead serviced facility
   c. Average restoration time per underground serviced facility

By overhead system is meant the electrical infrastructure such as substations and distribution lines that are above ground. By underground system is meant the electrical infrastructure such as substations and distribution circuits/cables that are underground and/or sheltered from the environment. In order to obtain a better perspective on the relative performance of overhead lines versus underground circuits/cables, and overhead substations versus those that are underground or sheltered, it may be useful to consider two sets of indicators, one for substations and the other for lines/circuits/cables. In the context of a distribution system, since lines/circuits/cables are the source of most power interruptions during extreme weather events (rather than substations), some utilities may want to focus exclusively on them. Furthermore, if a circuit contains both design types, overhead and underground, the utility would need to categorize it based on which particular type of design is dominant in the circuit in terms of its exposure to inclement weather conditions or treat it entirely differently as a special case.

The above resiliency measures/indicators are also shown in Table 3 below. Reporting on these measures by electrical utilities following every extreme weather event would allow them to compare their relative performance as well as develop plans and programs for various system hardening, upgrade and emergency preparedness initiatives. The same information can also be used by governments for policy creation and by energy regulators for developing regulation mechanisms that would require utilities to meet a minimum level of resilience performance, with penalties for not meeting and rewards/incentives for exceeding/meeting the level.

Table 3 Post-extreme event investigation (PEEI) spreadsheet. The PEEI is designed to assess the damage and review the performance of the system and its recovery.

		All Customers		**Critical Customers**	
		Overhead Service	*Underground Service*	*Overhead Service*	*Underground Service*
Electrical Infrastructure	*% Split: Overhead vs Underground (based on length)*	60%	40%		
Normal Modus Operandi	*% of Customers*	70%*	30%	40%	60%
Outage due to Severe Weather	*% of Customers without power at peak of event*	40%	15%	20%	3%
	Restoration (in hrs since event) of 50% of Customers	5	10	2	5
	Restoration (in hrs since event) of 80% of Customers	11	13	4	7
	Restoration (in hrs since event) of 100% of Customers	14	17	6	11
	Average Restoration Time (in hrs. since event)	10	13.3	4	7.6

* All numbers here are fictitious and serve as an example only

Since key resiliency measures/indicators suggested above are meant to be at a high level (for performance reporting and comparison purposes), it is envisaged that electrical utilities would develop more granular sub-measures for each key measure that would allow them to take tangible steps in the areas of planning, design and operating and measure tangible progress and take corrective measure as needed, so as to ultimately improve their resiliency performance and meet certain targets. More specifically, the sub-measures for electrical utilities would include and involve critical areas such as asset hardening, circuit/feeder topology, asset condition, emergency preparedness, field crew deployment, and allocation of spares.

Benefit can be derived by completing the above table as part of the standard protocol of all utilities following an outage due to severe weather. The table illustrates this procedure with fictitious numbers of a PEEI and can serve as a tool for performance analysis and measuring resiliency. Similarly, a Resiliency Checklist (see Table 4) was also created that identifies different actions that can be undertaken to increase resiliency of the electric system. The table represents only the basic outline of the idea at a high level. We suggest that the table and protocol be expanded (with sub-measures) and adapted to fit the needs of a utility. The three columns represent the three areas within which resiliency can be improved: prior, during and after an outage. That is, hard resilience, smart resilience and societal resilience. Hard resilience is the hardening of assets. Smart Resilience introduces new technologies that stimulate self-healing or fault detection measures. Perhaps the least tangible one is the societal resilience; it concerns the interaction with humans, such as emergency preparedness workshops of having the right crew at the right location etc.

Other supporting measures can be developed, as noted above, to enable electrical infrastructure planners and operators to plan, operate and maintain the electrical grid in a way that demonstrate improvement in different areas such as asset condition, emergency preparedness, field crew deployment which would lead to improvement in resiliency measures noted above.

Table 4 Resiliency/Resilience Checklist.

	Hard Resilience	Smart Resilience	Societal Resilience
Preparedness and Prevention	• N-2 or N-3 Redundancy • Location of infrastructure	• Micro grid • Weather forecast models • Smart technology • Load forecast	• Emergency response (ER) workshops • Location of emergency crew • Education and Awareness • "shelters"
Recovery	• Replacement • Vegetation Control	• Fault detection • Replacement • Upgrading	• ER protocol • Back up power and storage
Adaptation	• Islanding • Distributed generation	• Stockpiling of spares • R&D • CDM	• Continuous updating of ER protocol and workshop

How is resiliency different from reliability?

First and foremost, it is important to know that a system can be reliable but not resilient, meaning that under normal range of circumstances, the performance of a grid can be well within the extent of expectation; however, significant portions of this system may breakdown during extreme weather causing widespread and extended power outages. Resiliency, therefore, tests a system's (e.g. the grid's) performance under abnormal circumstances (i.e., under extreme weather, cyber-attack, etc.).

According to the European Copper Institute, reliability is a statistical number derived from a combination of historic experience and relatively short-term performance tests on an electrical system. In other words, a reliable power system is one that has a high availability - the proportion of time that the system is actually available to do real work (European Copper Institute) - whereas a resilient system is one that can withstand a number of sub-system and components failures while continuing to operate normally. This can be achieved by installing additional equipment –

redundancy – together with careful design – eliminating single points of failure - and well planned maintenance.
The reliability of an electric grid is measured in terms of the frequency and duration of power outages and is often indicated by:

- SAIDI: System Average Interruption Duration Index (minutes of sustained outages per customer per year)
- SAIFI: System Average Interruption Frequency Index (number of sustained outages per customer per year)
- CAIDI: Customer Average Interruption Duration Index
- MAIFI: Momentary Average Interruption Duration Index (number of momentary outages per customer per year)
- CEMI: Customers Experiencing Multiple Interruptions
- CELID – X: Customers Experiencing Longest Interruption Durations (longer than X hours)
- CEMMI – X: Customers Experiencing Multiple Momentary Interruptions (each longer than X hours)
- Sustained outage metric – measures the percentage of customers experiencing multiple outages

Resiliency of an electrical grid is normally defined as its ability to withstand extreme events and be able to recover from it or bounce back in a relatively short period of time. The damage due to the extreme event may include any or all of the following at one location or multiple locations in the system: poles & wires (i.e., circuits/feeders), communication system, IT system, human resources.

How are electrical grid reliability measures shifting in light of extreme weather?

The WeatherWise Partnership recognizes that electrical power is critical to many sectors (e.g., Telecommunication, Transport, Water Supply and Treatment). Likewise, the electrical sector has certain dependencies on other sectors (Roads, Urban Forestry to trim tree branches overhanging, Logistics and Supply Chains).

According to David MacLeod, Senior Environmental Specialist for the City of Toronto Environment and Energy Division, WeatherWise Partnership projects have included:

- A benchmarking study on electricity sector extreme weather resiliency efforts in other jurisdictions.
- A survey of Greater Toronto and Hamilton Area critical infrastructure and service providers tolerance to power disruption.
- A seminar for the electrical sector on climate change risk assessment including a demonstration of the Toronto Climate Change Risk Assessment Tool.

- Support for a Pilot Climate Change Engineering Vulnerability Assessment of a small portion of the Toronto Hydro electrical grid applying the Engineers Canada Public Infrastructure Engineering Vulnerability Committee protocol.
- Support for a system wide Climate Change Engineering Vulnerability Assessment of the Toronto Hydro electrical grid applying the Engineers Canada Public Infrastructure Engineering Vulnerability Committee protocol.

At a meeting of the WeatherWise Partnership on May 15, 2012, on behalf of the electrical sector involved with the Weatherwise Partnership, it was stated that if new extreme weather worst case scenarios are identified, the electrical sector needs to determine any new significant risks to the electrical system. Electricity sector organizations such as the IESO, Toronto Hydro and Hydro One plan, construct and operate the power grid to standards that reflect known extreme weather situations (extended heat wave is another example). This work is a core business function for the sector.

At the same meeting on behalf of the electrical sector it was also noted that with climate change, the frequency and magnitude of some extreme weather parameters may have changed or will change in the future. To understand the probability of future electricity power system failures as a result of climate change, the sector needs to develop an understanding of and the probability and magnitude of extreme weather scenarios based on best available climate records and climate models in Ontario.

Section 3: Weather Extremes and Projections

One of the most important considerations while taking concrete steps for increasing resilience of the electricity systems is having reliable weather and climate data. Weather and climate data is hard to forecast with 100% probability because of the numerous variables and impacting conditions involved. 70% of the earth is covered by water and this has a great impact on the temperature and climate around the world. Thus climate models often factor in atmospheric weather, ocean circulations etc. in their models. Physics based scientific models are now used to forecast weather patterns. This solid scientific basis gives a strong reason to believe that the models are a useful tool for exploring the behaviour of the climate system and its response to changes to external forces such as increases in greenhouse gas concentrations.

Climate models aim to create forecasts of climate behaviour that resembles the behaviour of the real climate system. The confidence that can be put on those aspects of model results that cannot be verified directly, such as projections of future anthropogenic climate change, is generally thought to increase with the closeness of this similarity. Important aspects of model predictions that make them credible are:

(i) The capacity of a model to simulate the present-day climate and

(ii) Its ability to simulate externally forced climate changes and variations based on different variables such as movement of clouds, CO_2 emissions, etc.

Different models are being used now for assessing climate change weather impacts[6]:
1. Atmospheric Ocean General Circulation Models (AOGCMs): focuses on large areas
2. Regional Circulation Models (RCMs): focuses on smaller areas
3. Earth System Models (EMICs): focuses on large time span

While many models exist, they are still unable to fully represent the intricate relationships between numerous variables that determine daily weather patterns. Due to limitations, the minimum grid spacing for data collection in AOGCMs ranges from 200–300 km. Thus weather developments acting on scales smaller than the grid spacing cannot be determined unambiguously. Hence this leads to the high level of uncertainty associated with prediction of local variations in climates by models (Raisanen, 2007).

Different infrastructures are impacted by extreme temperatures; however, we are first concerned about those considered critical such as the electrical grid, water treatment plants, sewers and culverts, public transport and roads. Thus, it is important to design these critical pieces of infrastructure to be able to withstand extreme weather conditions. Resilient infrastructure planning needs correct and reliable weather data, specific to a small region, such as a city. The focus of global and regional climate models on climate averages are unlikely to provide cities, such as Toronto, with adequate insight into extreme weather projection/changes necessary for prudent infrastructure management. Thus, special weather models, with more granular data and higher ability to predict extreme weather scenarios for a small area, is of extreme importance.

The Toronto's Future Weather & Climate Drivers Study uses a sequential combination of these models. Results from global and regional models were fed into the Weather Research Forecasting (WRF) model of much finer spatial resolution to provide detailed estimates of Toronto's future local weather between 2040 and 2049 – a period of time that City Officials plan for in terms of infrastructure replacement. The result is a climate-weather model at a resolution (1 km^2). This allows different climate and weather projections to be established for even small areas within Toronto (e.g., equivalent in area to small individual postal code areas or smaller areas within Scarborough, North York or Downtown) rather than only large regional areas such as southern Ontario or even the entire province or country.

[6] http://www1.toronto.ca/city_of_toronto/environment_and_energy/key_priorities/files/pdf/tfwcds-chapter4.pdf

Table 5 Comparison of different studies on weather changes in the future

Study/Source	Method	Predictions to note for North America
Toronto's Future Weather & Climate Drivers Study[7]	AOCGM + RCM Resolution: 1 km^2	More consecutive days of high temperature, more precipitation including ice storms
IPCC[8]	Historical data + AOGCM+ EMIC	Temperature rise of 3-4 degrees by end of century with business as usual scenario
NASA[9]	AOGCM	More forest fires, droughts and melting of arctic ice

All these studies identify some common parameters that are important/critical for reliability and resilience. Such parameters are as follows: Temperature, Humidity, Rain, Ice, Wind, and Consecutive days of high/low temperature.

Future predictions for Toronto (2040-2049):

- Less snow and more rain during the winter
- Slightly more precipitation (snow and rainfall) overall
- Precipitation amounts remain similar to present for about 8 months of the year
- Precipitation increases markedly in July and August (with 80% and 50% increases respectively over present values)
- The number of days of precipitation per month decrease (except in July and August)
- Fewer snow days per year
- Extreme rainstorm events will be more intense
- Large increase in size of extreme (daily) rain events in July (almost threefold)
- Average annual temperatures increase of 4.4^{o}C
- Average winter temperatures increase by 5.7^{o} C
- Average summer temperatures increase by 3.8^{o} C

Thus going by the future predictions resilience needs to be improved regarding the following weather phenomena: increased precipitation, floods, more consecutive days of high temperature, ice storms

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[7] http://www.toronto.ca/legdocs/mmis/2013/pe/bgrd/backgroundfile-55150.pdf
[8] http://www.grida.no/climate/ipcc_tar/wg1/pdf/wg1_tar-front.pdf
[9] http://www.nasa.gov/press/2015/january/nasa-determines-2014-warmest-year-in-modern-record

These weather conditions impact equipment of the electricity system in the following way compromising its ability to carry out its intended function:

Table 6 Effect on equipment and load due to different extreme weather phenomena

Weather Parameter	Grid Equipment			Load
	Outdoor Transformer	O/H Line	U/G Line	
Humidity				✓
Ambient Temperature	✓	✓	✓	✓
Ice		✓		
Wind		✓		
Rain			✓	
Wind/Rain		✓		
Ice/Wind		✓		
Wind / Temperature	✓	✓		✓
Humidity/ Temperature	✓	✓		✓

Section 4: Impact of Weather Extremes on Electrical Infrastructure

How do weather extremes reduce and/or violate safety margins?

The following extreme weather conditions affect the electricity system in the ways described below:

- Accelerating sea level rise: This can cause damage to electricity generation systems, flooding stations, etc.

- Increasing wildfires: The increasing wildfires cause damage to equipment.

- More frequent and intense heat waves: Consecutive days of high temperature affect equipment, reducing natural cool-down period and this leads to conditions exceeding the design limit for safety and then failure follows.

- Increasing incidence of flooding, ice storms and other extreme weather phenomena: These impact the overhead transmission lines leading to breakdown. They also impact load due to higher heating needs.

- Droughts and reduced water supplies: The electricity sector is highly dependent on water for generation and also cooling, especially in Ontario where hydropower and nuclear power are the leading sources of production. Hence, as temperatures continue to rise, droughts and reduced water supplies are likely to become the norm in some regions, increasing the risk to the power sector and causing loss due to reduced ability to produce (Vine, 2012).

- Elevated water temperatures: Water in lakes, rivers and reservoirs are used by power plants for their cooling needs. If the temperature of incoming water is too hot, or if the temperature of the discharge water is too high, power plants must dial back production or shut down temporarily, as has occurred at numerous coal and nuclear power plants over the past decade (Union of Concerned Scientists, 2012).

Figure 6 best explains the changes in temperature and the shifting mean of the curve.

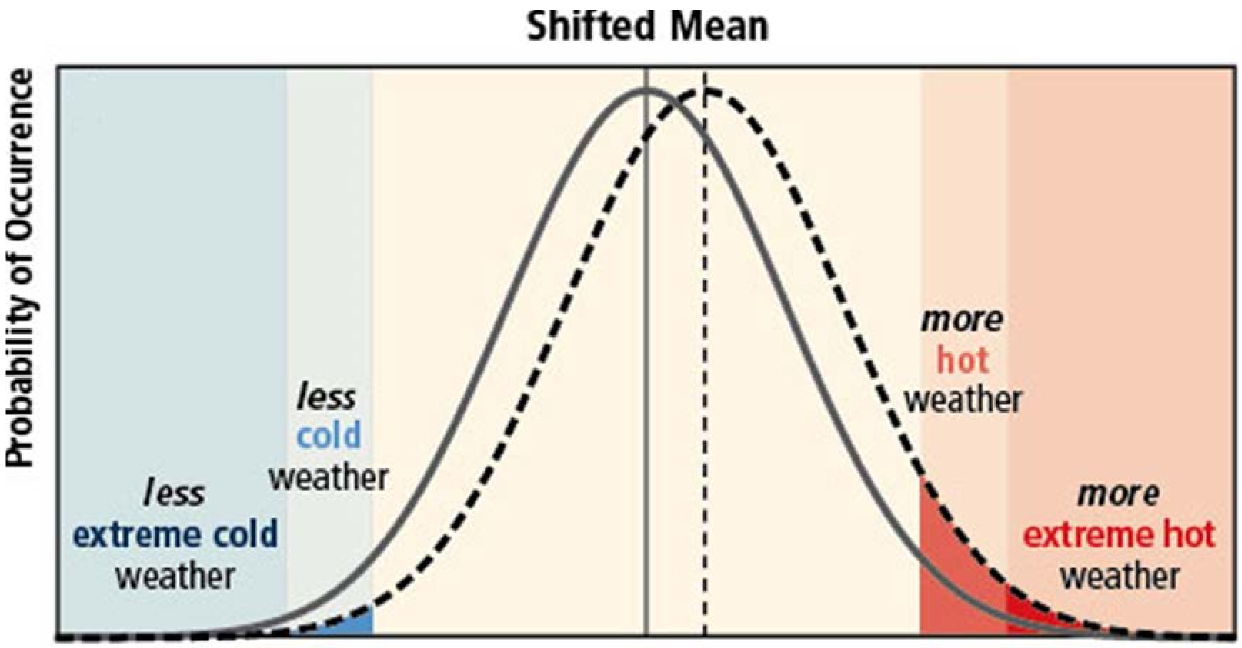

Figure 6 Shifted temperature and weather means due to climate change (Source: IPCC, 2012)[10]

With the change in weather normal, the design limits of different equipment and infrastructure will likely need to be modified as well. The new design limits will have to be geared to withstand extreme ranges in temperatures for longer periods of time.

Figure 7 Design margins affected due to extreme weather (adapted from: PIEVC, 2013)[11]

[10] http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf
[11] https://www.pievc.ca/sites/default/files/th_pievc_cc_assessment_final_external_june_1_2015_-_sep_14_revision_web.pdf

Resilience gaps in current electricity systems:

- Increasing severity of storms, which the current electricity generation, transmission and distribution systems are unable to handle
- High-rises (buildings) with no back up power creating vulnerable population easily affected by outages
- Bulk generation leading to large number of customers being affected in case of a breakdown
- Critical communications system vulnerability
- Education and awareness needs to be augmented both for the general public as well as various industries, ranging from healthcare to architects and urban planners.

Avenues for increasing resilience in electricity systems:

- Making equipment more robust by increasing the design limit
- Expanding demand reduction programs to reduce peak demand on the network
- Developing a smart grid for greater flexibility and responsiveness
- Reducing greenhouse gas emissions in energy generation
- Promoting distributed generation and renewable energy technologies

Figure 8, below lists ways to increase resilience of the electrical grid to withstand different natural phenomena.

Factors affecting resilience of electrical grid	Impact	Measures to increase resilience
Extreme temperatures 	Equipment malfunction	• Reducing demand through CDM measures • Using equipment with higher design limit
Storms 	Breakdown of transmission and distribution power lines	• Micro-grids to isolate sections of the grid • Sensors for fast detection of failures • Communities having generation backup • Individual storage availability
Droughts 	Reduction in water level affecting hydro generation	• Generation backup using renewable technologies • Using methods to stop evaporation from reservoir
Floods 	Breakdown of generation stations, power lines	• Not building generation and transmission stations in low lying areas • Adding backup

Figure 8 Measures to increase resilience in face of different adverse weather and climate phenomena

Section 5: Gaps and Actions in Achieving Electrical Infrastructure Resiliency

Thus the main issues are:

- Defining resilience (see Section 1)
- Predicting extreme weather (see Section 4)
- Creating a business case and financing resilience initiatives

It is important to clearly identify the business practicality or funding resilient increasing initiatives and taking necessary precautions to weather adverse climatic conditions. The Clean Energy Group (CEG) has published a paper on this funding challenge, called Financing Options for Clean, Resilient Power Solutions[12]. The diagram below represents the different funding options suggested by the report.

Figure 9 Financing resilience initiatives

The figure identifies four different methods of financing avenues for building the next generation infrastructure that is resilience and sustainable. Many different models are developing in North America, such as the clean energy fund introduced in New York, etc. The examples below illustrate the interesting and noteworthy efforts in other parts of USA being adopted to increase resilience of the electrical system.

A lot of work is being done in the United States for making their electricity grids more resilient. This is a direct impact of hurricane Sandy which caused mass devastation. With climate scientists forecasting more such storms in the future, increasing the resilience of the grid becomes an

[12] http://www.cleanegroup.org/assets/Uploads/CEG-Financing-for-Resilient-Power.pdf

immediate concern. Different initiatives are being deployed to better manage such a weather event. New Jersey is taking many initiatives to ensure resiliency is increased and to avoid breakdown of services during extreme weather events. TransitGrid is a first-of-its-kind microgrid capable of keeping the power running when the electric grid goes down. The NJ TransitGrid will not only generate power on-site but will incorporate a range of clean energy technologies such as renewable energy, energy storage, and distributed generation[13].

Maryland Utility - Baltimore Gas & Electric (BGE) had deployed 100,000 smart meters which helped in bringing back power faster after superstorm Sandy by identifying the exact location of power failures. The utility calculated it had saved more than $1 million by more efficiently deploying line workers and reducing labor costs along with lower truck deployments[14].

There are many other such improvements being made to the grid, making it more resilient. Technology hardening is one of the easiest ways of dealing with more extreme environmental conditions. Along with technological improvements we also need changes in policy to successfully meet future challenges.

Section 6: Suggested Path Forward for Toronto/Ontario EIPOs

What specific actions need to take place in the short-term, mid-term and long-term?

1. **Adapt to the unavoidable consequences of climate change (short-term, mid-term)**. To reduce the likelihood of power outages in the future, we must prepare for the risks we currently face starting with low-hanging fruits. This may later include spending money upgrading equipment, burying distribution lines, etc., but these approaches are often expensive and thus a business case needs to be developed on a project by project basis.
2. **Reduce the problem by reducing demand (short-term and onwards)**. Creating energy efficient building, adopting conservation practices, etc., can reduce the need to build new generating stations and reduce greenhouse gas emissions.
3. **Conduct vulnerability assessments (short-term)**. Cities, counties, and provinces/states should conduct thorough assessments to evaluate the risks of climate change on their electricity infrastructure. Incorporate climate adaptation and mitigation measures into utility resource planning. State/provincial and local governments should require utilities to

[13] http://www.njtransit.com/tm/tm_servlet.srv?hdnPageAction=PressReleaseTo&PRESS_RELEASE_ID=2884
[14] https://www.greentechmedia.com/articles/featured/How-Utilities-Are-Using-New-Technology-to-Protect-the-Grid

consider the costs of adapting to and mitigating climate change impact in their long-term planning.

4. **Upgrade electricity infrastructure (mid-term, long-term).** Power plan should install technologies that use less water. Utility and grid operators should pursue approaches that make the grid more flexible and better able to integrate renewable energy sources. These include increased energy storage capacity, adopting demand-response programs, and developing micro-grids to better isolate outages.
5. **Strengthen clean energy policies (short-term, mid-term)**. Provincial and federal policy-makers should adopt and strengthen programs that support the timely expansion of renewable energy and energy efficiency measures, such as renewable electricity standards.

How to create a framework for assessing and increasing resiliency of energy systems?

- Getting reliable and valid data to create as accurate forecasts as possible
- Creating scenarios using forecasts with different probabilities
- Spreading awareness to the consumer to induce behaviour modification leading to better demand management
- Engaging the regulator
- Conducting risk assessment of impact on infrastructure
- Conducting a standards review and suggesting modifications
- Creating a business case

Table 7 Technological and policy changes required to increase resiliency of electricity system

	Technological advancement required	Policy changes required
Short-term	Flood protection	Change in building code
	Storage units which are affordable	Support to distributed generation and community energy projects
	Wide scale distributed energy generation	Reduction in demand through conservation and demand management programs
Long-term	Back-up power to important services	Training customers to better adapt during failure of service
	Micro-grids and increased use of sensors for failure detection	Increasing bottom up decision making to create unique solutions for different communities

Section 7: Conclusions

During the course of the research project, some quotes from our interviews which support the current understanding of the term resilience are as follows:
"Resilience is not something that can be 'fixed', it can only be improved."
"Resiliency is still a work in progress."

Resilience is hard to define, as it often comes into play only after an extreme event, be it natural or manmade which is not the norm and hence, is often a scenario un-planned. These events can then cause huge amounts of damage both monetary and social. The changes required to current systems to make them resilient, especially the electrical power systems, would seem to be high inter-disciplinary requiring changes to codes, standards, equipment design, planning parameters, citizen participation, etc.

The first step to increasing resilience is securing reliable weather forecasts for extreme weather. New extremes need to be defined, and existing planning, design and operating parameters need to be modified. Risk analysis to identify vulnerabilities is required followed by establishing new criteria for system design.

Figure 10 identifies the important approaches needed to determine gaps and to increase the resilience of the system.

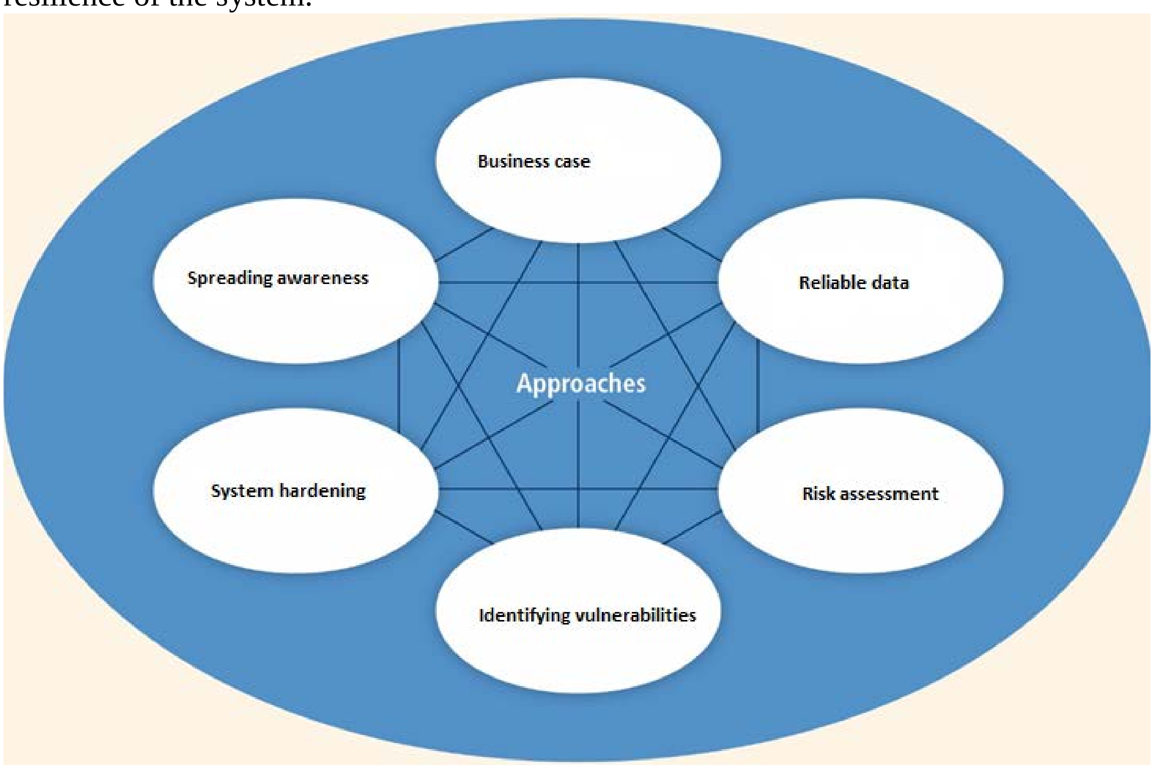

Figure 10 Approaches to increase resilience of a system

A point to be noted is that the resiliency measures/indicators proposed in this paper are for the distribution level of the electricity system that is directly serving the consumers and exclude the impact of the upstream transmission system. However, when a portion of the transmission system goes down during an extreme event rendering the distribution system it serves without power, the distribution system to some extent can be reconfigured and restored with power if appropriate switching devices are placed within the distribution system and another supply point from the upstream transmission system exists. This highlights the mutual dependency of transmission and distribution and the need for the two groups of planners and operators to work together to a common goal of achieving higher resiliency.

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