Climate Risk Management Approaches in the Electricity Sector: Lessons from Early Adapters

Pierre Audinet, Jean-Christophe Amado and Ben Rabb

Abstract Climate change adds a new source of unknowns for the electricity sector. Despite considerable risks and opportunities, energy sector actions to manage climate change risks and take advantage of future opportunities remain limited and patchy. An estimate of the sums spent since 2000 and planned out to the 2020s by five utilities on climate risk management totals US$1.5 billion. Considering that these investments are to address climate change risks or opportunities of a considerable magnitude, they are relatively modest. The sector hasfocused on climate data analysis and research on impacts rather than on concrete capital, technological and/or behavioral adaptation responses. Further, most of this research is concentrated for the most part in the developed world and on a handful of climate change impacts. Analysis of early adapters in the electricity sector offers a number of useful lessons for power utilities, regulators and stakeholders in thedeveloping world, for instance: (i) joint efforts between the electricity sector and hydrometeorological offices to develop high quality and tailored climate data and information are needed to avoid 'wait-and-see' strategies among power

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P. Audinet (✉)
ESMAP–World Bank Group, Washington DC, USA
e-mail: paudinet@worldbank.org

J.-C. Amado
Deloitte (formerly Acclimatise), 100 Queen street, Ottawa, Ontario, K1P 5T8, Canada
e-mail: jamado@deloitte.ca

B. Rabb
Acclimatise, Pascoe House, 54 Bute Street, Cardiff Bay, Cardiff CF10 5AF, UK
e-mail: b.rabb@acclimatise.uk.com

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utilities; (ii) energy sector adaptation requires going beyond high level research on impacts and adaptation to produce information that can be applied operationally; (iii) without a business environment favorable to climate change adaptation, power utilities have little incentive to go beyond 'business-as-usual' weather risk management; and (iv) it is by building the economic case for adaptation that utilitiescan be incentivized to take action.

Climate change adds a new source of unknowns for electricity sector decision makers. Currently, use of present-day or historical weather and seasonal climate data and information is part of everyday risk management for many utilities and regulators across the world. However, the integration of forward-looking information on climate change in decision-making known as 'climate change adaptation' remains limited. Yet, long-term changes in climate and short-term increases in climate variability are increasingly impacting generation, transmission and distribution of electricity, forcing the industry to consider new ways to manage the associated risks. In some cases, climate change creates opportunities for the electricity sector, for example increased hydropower generation potential in the near- to medium-term in glacial-fed river basins.

This chapter takes stock of initiatives to assess those risks and manage future impacts based on interviews with five utilities, one power regulator and electricity one industry association, and a review of published energy sector information. The purpose of this chapter is to extract lessons with a particular focus on what can be learnt for developing countries where progress to date on managing climate change risks and opportunities is lagging behind. This chapter builds upon the work of the World Bank Energy Sector Management Assistance Program (ESMAP) on energy sector vulnerability to climate change. In 2010, ESMAP and the World Bank's Global Expert Team for Adaptation published a compendium of what is known about weather variability and projected long-term changes, and their impacts on energy systems.

Overall, the electricity sector is at a very early stage of its "climate change adaptation journey." Research on climate data and information, risks and adaptation solutions is concentrated, for the most part, in the developed world and on a handful of climate change impacts. Considerable uncertainties remain about the likelihood, severity, and timing of these impacts for the electricity sector industry. Adaptation responses in the electricity sector remain patchy. Utilities have started investing in adaptation to reduce climate change vulnerability, avoid some future impacts, or seize future opportunities. A rough estimate of the capital expenditures for climate change adaptation since 2000—and presently planned up to the 2020s—by six large electricity utilities surveyed[1] amounts to a cumulated US$ 1.5

[1] Authors interviewed China Light and Power (China), Electricité de France (France), E-ON (Germany), ESKOM (South Africa), Hydro-Québec (Canada), National Grid (United Kingdom) by email and phone.

billion. Considering that these investments address future climate impacts or opportunities potentially of a considerable magnitude, those investments are relatively modest. For instance, the repair costs for hurricane Isaac which hit southeastern United States are estimated to have reached around $400 million for Entergy alone in four states (Arkansas, Louisiana, Mississippi and New Orleans) for Entergy alone. This suggests that there could be a strong business case to scale up climate change adaptation investments in the electricity sector.

Four lessons are drawn from this stock-taking exercise.

1. *Joint operations between the electricity sector and hydrometeorological offices to develop high-quality and tailored climate data and information are needed.* Electric utilities require data and information on observed and future climate conditions on a range of timescales, spatial resolutions, and statistical variables other than climatic averages. Currently such data and information are often not immediately available, which often leads to a "wait-and-see" attitude in the industry. Evidences point to a limited engagement of the electricity industry with the producers of climate scenarios and meteorological institutions.

2. *Electric utilities, regulators, industry associations, governments, and the academic world need to coordinate the expansion of the knowledge base on climate change risks and adaptation solutions in the electricity sector.*
   A lot of the information available on climate change impacts and adaptation is too aggregated to be of direct use in the electricity sector's operations. Too few utilities are doing work to identify cost-effective adaptation measures based upon assessments of material risks for generation, transmission and distribution infrastructure.

3. *Governments, international institutions, and professional bodies can incentivize measures that build resilience against to future climate change in the electricity sector by developing standards, regulations and technical guidance.*
   The majority of today's climate change adaptation responses in the electricity sector are usual risk management measures that are strengthened by considering how the climate is changing. There are very few examples of "new" technological, behavioral, or institutional measures implemented solely to manage future climate change impacts.

4. *Industry and government need to support research to raise awareness on the nature and possible range of future industry costs with and without adaptation, as well as on the methods and tools to take into account uncertainties in climate change adaptation planning and cost-benefit analysis.*
   The ability to build a strong economic case for climate change adaptation remains constrained by a number of factors: lack of reliable climate data and information, low confidence in the return on investment of adaptation expenditure due to multiple uncertainties, and short-termism.

1 The Need to Strengthen the Climate Change Resilience of Electricity Systems in Developing Countries

Natural resource endowment for electricity production (such as river runoff, wind, and solar radiation), transmission and distribution, and electricity demand are all sensitive to weather conditions, climate variability, and long-term changes in climate (see Table 1) (Ebinger and Vergara 2011; European Observation Network, Territorial Development, and Cohesion 2010; Troccoli 2009; Williamson et al. 2009).

However, little is known about what potential impacts will constitute material risks for electricity regulators or utilities, regulators and stakeholders (such as customers). Some impacts have the potential to affect electricity system reliability, security of supply, affordability, and environmental performance (including greenhouse gas emission reductions), while others will have very little effect on electricity assets or systems (Ebinger and Vergara 2011; European Observation Network, Territorial Development, and Cohesion 2010; Troccoli 2009; Williamson 2009). Existing literature shows that integration of climate change information in energy sector decision-making remains limited, for the most part, to large-scale electricity infrastructure in developed countries (Urban and Mitchell 2011).

Due to a combination of several factors, electricity systems in developing countries are particularly vulnerable to a changing climate. First, in many countries, the electricity sector is highly sensitive to weather variability and extreme events. For example, in 2005 alone, extremely hot and cold weather explained 13 % of the variability in energy productivity[2] in developing countries, though much of this variability remains unexplained (MacKinsey 2009). Countries that have repeatedly experienced difficulties maintaining a reliable electricity supply in the past due to weather conditions or that routinely suffer considerable financial loss due to extreme weather events are at risk from climate change (Mechler 2009). Second, high reliance on hydropower, design and construction of power assets on the basis of poor hydrometeorological data, presence of aging assets, and insufficient infrastructure compared to existing needs all constitute factors of climate change vulnerability (Ebinger et al. 2011). This means that many electricity systems are not even adapted to present-day climate, let alone future climate. Finally, developing countries have low capacity to improve their resilience. For example, only a small percentage of costs due to natural disasters are absorbed by insurance in developing countries (International Institute for Applied Systems Analysis (IIASA) 2010). Utilities often have limited ability to finance capital investments, electricity systems often operate with no or few interconnections with other systems, and access to high-quality hydrometeorological and climate data is often poor (Veit 2009).

[2] Energy output divided by energy consumed (aka "supply-side efficiency").

Table 1 Electricity sector vulnerability to climate change

Electricity sector value chain	Relevant climate impacts			Impacts on the energy sector
	General	Specific	Additional	
Resource endowment				
Hydropower	Runoff	Quantity (+/), seasonal high flows and low flows, extreme event	Erosion, siltation	Reduced firm energy, increased variability, increased uncertainty
Wind power	Wind field characteristics, changes in wind resource	Changes in density, wind speed, increased wind variability	Changes in vegetation (might change roughness and available wind)	Increased uncertainty
Solar power	Atmospheric transmissivity	Water content, cloudiness, cloud characteristics	Pollution/dust and humidity absorb part of the solar spectrum	Positive or negative impacts
Wave and tidal energy	Ocean climate	Wind field characteristics, no effect on tides	Strong linearity between wind speed and wave power	Increased uncertainty, increased frequency of extreme events
Supply				
Thermal power plants	Generation cycle efficiency, cooling water availability	Reduced efficiency, increased water needs (e.g., during heat waves)	Extreme events	Reduced energy generated, increased uncertainty
Hydropower	Water availability and seasonality	Water resource variability, increased uncertainty of expected energy output	Impact on the grid, wasting excessive generation, extreme events	Increased uncertainty, revision of system reliability, revision of transmission needs
Wind power	Alteration in wind speed frequency distribution	Increased uncertainty of energy output	Short life span reduces risk associated with climate change, extreme events	Increased uncertainty on energy output
Solar power	Reduced solar cell efficiency	Solar cell efficiency reduced by higher temperatures	Extreme events	Reduced energy generated, increased uncertainty

(continued)

Table 1 (continued)

Electricity sector value chain	Relevant climate impacts			Impacts on the energy sector
	General	Specific	Additional	
Transmission and distribution	Increased frequency of extreme events, sea level rise	Wind and ice, landslides and flooding, coastal erosion, sea level rise	Erosion and siltation, weather conditions that prevent transport	Increased vulnerability of existing assets
Demand	Increased demand for indoor cooling	Reduced growth in demand for heating, increased energy use for indoor cooling	Associated efficiency reduction with increased temperature	Increased demand and peak demand, taxing transmission and distribution systems
Support or connected infrastructure, and local communities	Competition for water resources, competition for adequate siting locations, transport disruptions	Conflicts in water allocation during stressed weather conditions, competition for good siting locations	Potential competition between energy and non-energy crops for land and water resources	Increased vulnerability and uncertainty, increased costs, increased disruptions

Source adapted from Ebinger et al. 2011

2 Existing Research on Climate Change Data and Information, Associated Risks, and Adaptation Solutions

2.1 Research on Climate Change Data and Information

Utilities, regulators and professional bodies in the electricity sector have initiated research efforts to improve hydrometeorological data and climate normals[3] used by electricity sector decision makers. The variables that have received attention are temperature, wind, rainfall, ice, snow, and runoff, because electricity regulators and utilities use information about these climatic factors to make planning, risk management, asset design, and operational decisions.

A lot of work is ongoing to improve observed data and future simulations for rainfall, ice, snow, and runoff in order to optimize hydropower plant asset design and operations. For example, Hydro-Québec has improved the capacity of its hydrological model to provide future runoff simulations that are driven by climate model projections. Such work has started to inform new asset design and the operation of existing hydropower plants (see Box 1). Hydro-Tasmania has also done work to assess future water inflows in a changing climate (Brewster et al. 2009). Canadian electric utility BC Hydro is working with university researchers to develop specialized weather prediction services for icing, precipitation, and lightning. Research is also underway to improve ice-loading forecasting systems (Musilek et al. 2009).

Box 1. Hydro-Québec

Hydro-Québec is one of the largest electric utilities in North America, with a total installed generation capacity of 36,671 MW and the longest transmission system in the US and Canada. More than 90 % of its installed capacity comes from hydropower installations. The company owns and manages 59 hydroelectric generating stations, 26 large reservoirs, 571 dams, four thermal and one nuclear power plants, 33 453 kilometers of electric lines and 514 electric substations. The company supplies electricity in Québec, Canada, and trades with other Canadian suppliers (in Ontario and New Brunswick) and US Northeast states.

Research to understand future changes in climate and impacts on water inflows

In response to a series of adverse weather conditions (the 1996 Saguenay-Lac-Saint-Jean flooding, the 1998 ice storm and drought conditions) that caught the attention of Hydro-Québec's executives and government,

[3] *Climate normals* are decadal or multidecadal datasets used to summarize or describe the average climatic conditions of a particular location.

Hydro-Québec developed a research program in 2002 to improve knowledge of future climate change, business impacts, and adaptation solutions in the mid- to long-term, so that risks can be managed and opportunities exploited. Joining efforts with the Québec government, Hydro-Québec set up a scientific consortium with the mandate to study regional climate, impacts and adaptation solutions: the Consortium on Regional Climatology and Adaptation to Climate Change (Ouranos). Hydro-Québec partly finances Ouranos by contributing annually CDN$1 million and 5 full-time equivalent researchers and engineers. As part of Ouranos, Hydro-Québec cooperates with other electricity producers (Rio Tinto Alcan, Ontario Power Generation, and Manitoba Hydro) on climate change risk and adaptation issues and has access to the data and information created by Ouranos.

Using its in-house hydrological model and climate change scenarios from Ouranos, Hydro-Québec produced an extensive set of future runoff projections for each of the watersheds where it has hydropower facilities. To increase the level of confidence in its projections, Hydro-Québec analyzed the sensitivity of its hydroclimatic simulations to the choice of greenhouse gas (GHG) emission scenario, climate model, hydrological model, and climate impact methodologies. This "multi-method" approach has shown that, for the 2050 time horizon, the choice of climate models influences hydroclimatic simulations much more than the choice of GHG emission scenarios, hydrological models, or methodology. Hydro-Québec has consequently revised its set of future watershed runoff projections, drawing upon a large number of climate change scenarios. Results are presented in Fig. 1.

Despite some uncertainty between climate models, these projections point at an overall increase in runoff by the 2050, with a higher increase in the north of the Québec province, where most of the company's production facilities are located, compared with the southeast. Projections also suggest more sustained winter inflows from November to April and reduced summer inflows. Furthermore, high river flows will occur earlier in the Spring due to increased temperatures and peak river flows will be lower on average due to reduced winter snow mass.

Hydro-Québec has planned further refinements to its hydroclimatic modeling. For instance, the company wants to:

- Analyze the role of Canadian bogs and fens in Northern Québec in water flow and balance.
- Improve the resolution of its future runoff simulations using direct outputs from regional climate model projections using dynamical downscaling techniques.

Hydro-Québec has started using these future runoff projections at an operational level. For example, the Equipment division assessed the impacts of climate change on hydrological conditions for the "Eastmain 1A—Dérivation Rupert" project. The results were presented at a public hearing to

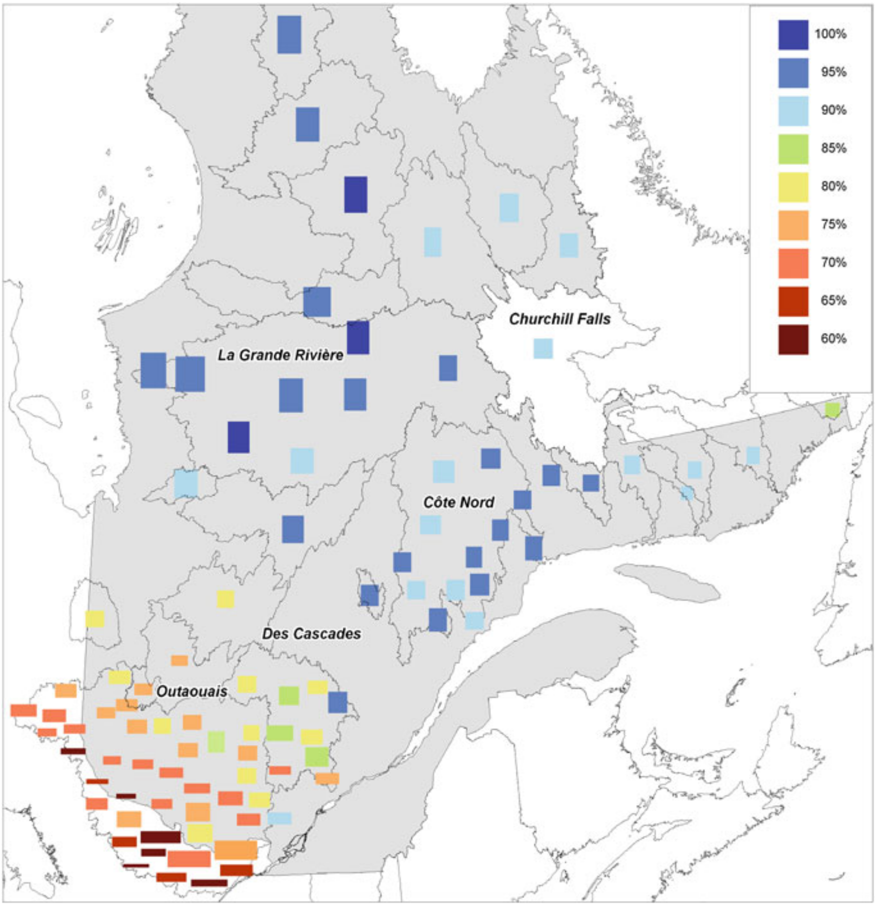

Fig. 1 Future runoff projections based on 90 climate change scenarios. Each *bar* represents results for one watershed; *height* indicates the amplitude of the future increase between 1970–2000 and 2040–2071; *width* indicates the difference in results between different climate change scenarios; and *color* indicates the degree of convergence between the different scenarios, in percentage of scenarios projecting an increase (*blue* for strong, *brown/red* for weak). *Source* Roy et al. 2008 (updated since to 94 watersheds and 90 climate scenarios)

answer questions from the public on the cumulative impact of climate change for fisheries (Comité Provincial d'Examen (COMEX) 2006).

The company is planning to use these runoff projections to assess the benefits associated with adapting the design of different hydropower infrastructure assets for both new equipment and the refurbishment of existing facilities.

Recognizing that the 1990–2000 decade was much warmer in comparison to the 1961–1990 time period, Hydro-Québec's Distribution division

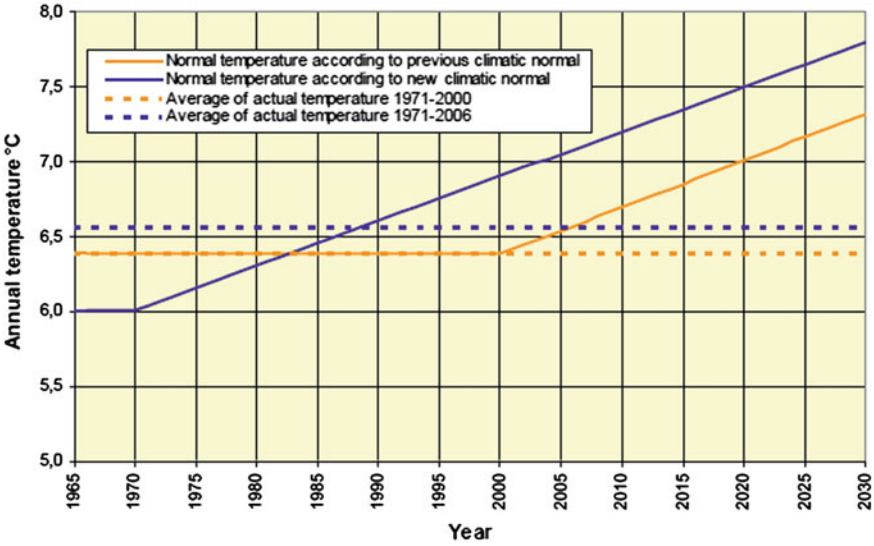

Fig. 2 Evolution of the annual temperature normal for Montréal after updating climate normals to include recent observations and the effect of climate change. *Source* Nadeau 2008

initiated work to update the climate normals it uses to forecast long-term electricity demand.

In 2007, working with the Consortium on Regional Climatology and Adaptation to Climate Change, Hydro-Québec updated the reference period of its climate normals to 1971–2006 and introduced a warming trend of +0.3 °C per decade into the calculation of its climate normals. That resulted in an increase in the average annual temperature normals for the city of Montréal of 0.51 °C for the period 2001–2030 (see Fig. 2). This increase reduced load energy requirements by almost 1 TWh (−0.5 %) per year as a result of reduced heating needs. Furthermore, Hydro-Québec had a 350 MW (−1 %) peak load reduction under the new climate normals. These reduced electricity demand forecasts impacted the required Hydro-Québec electricity production rate and the 10-year procurement plan, which were approved by the Québec regulator.

Incorporate risk management into Environmental Impact Assessments (EIA)
Hydro-Québec considered the effect of future climate change on hydrological regimes as part of the EIA for a new hydroelectric development in Québec, Canada ('Complexe La Romaine'). This helped Hydro-Québec understand future runoff changes and the implications for hydropower production optimization and operational safety.

Using future climate projections, the EIA found that annual average runoff could increase by up to 19 % by 2050 compared to 1961–1990. Considering that current design standards already take into account a high interannual and monthly variability of water inflows, Hydro-Québec concluded that the projected impacts of climate change could easily be managed thanks to adaptive management measures, for example adapting operating rules.[4] The Canadian Environmental Assessment Agency approved this approach in a report of April 2008.[5]

Electric utilities and regulators usually rely on normalized average temperature to forecast customers' future electricity needs, which influences long-term supply/demand balance and investment plans up to 20 years in the future. Though different methods are used, the North American power sector usually uses 30-year average temperature datasets from government organizations, such as the US National Oceanic and Atmospheric Administration or Environment Canada. However, these datasets seldom take into account future temperature rises, which could affect the reliability of demand forecasts. Some climate data providers, electricity regulators, and utilities are developing alternative methods or climate datasets, to better take into account future climate variability: (Electric Power Research Institute and (EPRI), North American Electric Reliability Corporation (NERC), and Power System Engineering Research Center (PSERC) 2008). Some organizations have started using more recent and shorter observed time periods or rolling decadal averages, which already reflect some degree of climate change (for example, Hydro-Québec, see Box 1). BC Hydro is also developing high resolution wind projections for British Columbia, to improve its wind forecast capability and management practices (Toth 2011).

2.2 Research on Risks Associated with Changes in Climate

Few organizations have taken steps to assess how future changes in climate or climate-related variables will likely affect their systems, operations, and assets.

2.2.1 Hydropower Generation

BC Hydro and Hydro-Québec have put considerable effort into simulating future water inflows (see Box 1). The companies plan to use this data in the coming years to estimate future electricity output, and inform asset design, potential changes in operations and long-term planning.

[4] See the environmental impact assessment for the La Romaine hydrolectric complex (Vol 7, Chap. 49, pp. 49–6 to 49–19), available at http://www.hydroquebec.com/romaine/documents/etude.html (accessed 12/09/2011).

[5] See http://www.ceaa.gc.ca/050/documents/26480/26480E.pdf (accessed 12/09/2011).

Hydro-Tasmania has modeled future water inflows into its reservoirs based on rainfall and evaporation projections. Results indicate lower annual inflows, changed runoff seasonality and an overall reduction in output, especially in run-of-the-river plants and in central Tasmania (Brewster et al. 2009).

2.2.2 Transmission and Distribution

Recognizing the risk of stronger winds for transmission and distribution, BC Hydro has begun to study the relationship between tree fall, transmission and distribution damage, and storm intensity, to better understand the risk of infrastructure damage (Toth 2011).

To comply with safety obligations, utilities must operate electric equipment and hardware below maximum design temperatures. Thermal ratings of electrical lines are calculated on the basis of ambient conditions (usually based on a long-term average), and maximum current that can be safely carried, in order to ensure that maximum design temperature is never exceeded. Higher average temperatures and changes in natural cooling (rainfall, wind, or cloud cover) could reduce current ratings and constrain transmission or distribution capacity (Pytlak et al. 2011; Toth 2011; National Grid Electricity Transmission plc. 2010; South West Climate Change Impacts partnership 2010). Several electricity sector groups have engaged in research showing future thermal de-ratings due to changes in climate conditions (Pytlak et al. 2011; Toth 2011; National Grid Electricity Transmission plc. 2010; South West Climate Change Impacts partnership 2010) (see the example of National Grid, Box 4). While this may not represent a risk for well-designed systems, it could be an issue in countries with aging assets operating close to their design ranges. Utilities wanting to keep electricity supply efficiency levels above a certain level have to consider the trade-off between the cost of upgrading line thermal rating and the price of electricity sold.

2.2.3 Demand Loads

The Electric Power Research Institute (EPRI), the North American Electric Reliability Corporation (NERC), and the Power System Engineering Research Center (PSERC) organized a technical summit on climate change and demand load forecasts in 2008, which called for strengthening climate change impact data collection and impact assessment methodologies, including methods to measure the benefits of increasing the adaptive flexibility of electric systems and compare those to the associated costs. (EPRI, NERC, and PSERC 2008). A number of electricity regulators and utilities, such as the Canadian Independent Electricity Operator, Hydro-Québec, and Electricité de France, have started revising their own demand load forecasting methods using climate model projections, in response to future higher temperatures and associated long-term electricity demand changes (see Sect. 2) (Mirza 2011; Dubus 2009; Minville 2009).

For example, the number of cooling degree days[6] in London, UK, increased by an additional 30–34 days over the period 1961–2006 (Jenkins et al. 2007). The UK project GENESIS (Generic Process for Assessing Climate Change Impacts on the Electricity Supply Industry and Utilities) found that by the 2080s summer electricity demand for cooling will exceed winter demand for heating during the daytime (Watson 2006). This will aggravate system overloading in certain parts of London, and will require additional supply responses.

2.2.4 Asset-Level Risks

Drawing on existing information on specific climate change impacts and adaptation measures, CLP Holdings and Eskom have assessed climate risks and identified adaptation measures for a few pilot assets, to build the business case internally for adaptation-related decisions, and improve operational risk management (see Box 2 and 3).

Box 2. CLP Holdings

For over 100 years, CLP Holdings, formerly known as China Light and Power, has played an active role in powering Asia's growth. From its home base of Hong Kong, CLP's operations have expanded to include mainland China, Australia, India, Southeast Asia, and Taiwan. As of 31 December 2010, CLP has invested in 13,635 MW of electricity generation (from a range of energy sources including coal, gas, nuclear, hydro, wind, solar, and biomass), 6,599 MW of generation capacity across the Asia–Pacific region, 22PJ of gas storage capacity in Australia, 13,767 km of electricity transmission and distribution lines, 13,421 substations in Hong Kong, and a number of electricity and gas retail businesses serving over 3 million customers in Hong Kong and Australia.

As stated in CLP's report *Climate Vision 2050,* the organization is committed to addressing climate change: "[CLP will] ensure that our business develops only commercially viable, environmentally responsible energy generation assets to meet rising market demand" (CLP's Climate Vision 2050). CLP has engaged on a "climate change adaptation journey" to address risks within the company's "fenceline." As shown in Table 2, CLP has identified a number of potential risks at a corporate-level.

Adaptation pilot study

CLP began to work with a specialist consultancy firm to understand the possible future impacts of climate change on its assets, with an initial pilot study focusing on two existing operations that have already experienced

[6] Cooling degree day (CDD) is the number of days when average temperature is above 65 degrees Fahrenheit/18 degrees Celsius and people start to use air conditioning to cool buildings.

Table 2 Corporate-level climate change risks identified by CLP in its response to the 2011 Carbon Disclosure Project investor survey

Risk driver	Description	Potential impact	Timeframe	Likelihood	Magnitude
Change in mean (average) temperature	Affects operations as demand for electricity for, say, air conditioning, will not follow established patterns	Increased operational cost	Current	Very likely	Medium
Change in temperature extremes	Affects operations as demand for electricity for cooling or heating could fluctuate dramatically	Increased operational cost	Current	Very likely	Medium
Change in precipitation extremes and droughts	Extreme precipitation could lead to flooding and drought could affect availability of process water	Increased operational cost	Current	More likely than not	Medium
Sea level rise	Our facilities that are located near the coast could be affected	Increased capital cost	Current	More likely than not	Medium–high
Tropical cyclones	Our facilities may not be built to sustain cyclones that have become stronger than historical events	Increased capital cost	Current	More likely than not	Medium–high

Source Carbon Disclosure Project website

physical impacts from extreme weather conditions. The main objective was to help the company to develop a methodology that can be applied across CLP for assessing what climate change adaptation measures can and should be taken from a business case perspective for existing operations, and perhaps provide some insight for possible future acquisitions or greenfield developments. The two pilot sites chosen comprised a gas-fired power station in India (GPEC) and a coal-fired power station in Taiwan (Ho-Ping), both located near coastal areas.

The potential loss arising from climate change was quantified for each site and adaptation options identified where possible. This was followed by a cost-benefit analysis of the various adaptation options and the testing of a decision-making process that involves not only taking mandatory regulatory requirements as “must dos”, but also CLP’s company values which dictate what it perceives to be the “right things”.

CLP analyzed the following sources of climate data and information to determine future climate scenarios: historical trends, local minima and maxima, Global Circulation Model (GCM) simulations, and regional climate projections.

Climate projections are useful for determining the direction of future changes, however they contain considerable uncertainties. Large-scale projections of future climate utilize Global Circulation Models (GCMs) to describe the physical circulation of the coupled atmosphere/ocean/land system. Furthermore, greenhouse gas emission scenarios are used to model a range of futures considering different global and regional driving forces. GCMs are highly sophisticated, however inherent uncertainties mean that the projections have to be applied with care. Regional climate maxima were used wherever possible to reduce uncertainty. However, as the Ho-Ping coal-fired power plant showed, history is not always a good predictor of the future, as future climate poses challenges outside historical experience. The study identified and assessed adaptation options to determine the most effective and efficient options in response to the identified risks.

Risk and adaptation findings

The coal storage domes and coal conveyor at the Ho-Ping coal-fired power station were designed to withstand wind speeds during typhoons of up to 60 m/s for a 3 s duration (CLP 2011). The strongest gust speed ever recorded at the time of design was 56 m/s. However, since asset construction, wind speeds have exceeded this threshold on a number of occasions, during which all three coal domes have experienced damage and caused coal supply disruptions. High winds associated with typhoons have also caused power outages on four occasions between 2005 and 2008. On each occasion, electricity output from the plant was lost, causing extended power cuts for customers. During typhoon Jangmi in September 2009, wind damage to transmission lines caused 17 days of outages.

Recent research suggested that on a global scale tropical cyclones will see an increase in intensity of between 2 and 11 % by 2100. Given a maximum historical wind speed of 89.8 m/s during Typhoon Alex in 1984, this could give rise to gust speeds of 100 m/s (CLP 2011). For the West Pacific, this figure could be even higher, given possible average projected increases of up to 20 % (Knutson et al. 2010). CLP also investigated the risk of landslides, erosion and high wind speeds to transmission lines infrastructure at Ho-Ping.

Similarly, climate risks were assessed for the gas-fired power station in India (GPEC), which is also vulnerable to tropical cyclones (see Table 3). In particular, GPEC was found to be at risk of saline intrusion and flooding as a result of storms and sea level rise. In the case of GPEC, a number of adaptation options have already been implemented, for example raising the floor level of buildings housing critical infrastructure, building flood levees around low-lying parts of the site, increasing drainage capacity, and

Table 3 Climate risks identified at Ho-Ping coal-fired power station in Taiwan, and GPEC gas-fired power station in India

Impact	Ho-Ping	GPEC
Wind	Coal dome and conveyor damage Transmission line outages	Damage to third party gas terminals
Erosion/ landslides	Transmission tower damage Fresh water supply cut-off	n/a
Coastal flooding	Coal conveyor damage Coal dome inundation	Damage to third party gas terminals reducing supply
Pluvial flooding	Coal dome inundation	n/a
Sea level rise	n/a	Fresh water salinity increase
Temperature increase	Cooling water temperature : increased heat rate and fuel cost	Ambient temperature : decreased output

Source CLP Holdings

diverting cooling water pipes to access fresh water in the event of saline intrusion.

In light of the risk assessment, the pilot study identified the following climate change adaptation options: (CLP 2011):

- Inspect tower on or close to erosion/landslide risk slopes;
- Commission a wave action study to estimate maximum wave height during typhoons;
- Reinforce the base of towers on landslide risk slopes;
- Reinforce the base of five towers close to landslide risk slope;
- Strengthen five towers and transmission line sections to withstand strong gusts;
- Investigate emergency coal delivery by rail;
- Reinforce coal conveyor cladding;
- Protect domes from water ingress;
- Reinforce fresh water pipeline/secure alternate sources; and
- Increase drainage capacity on-site.

Conclusions

Climate change poses site-specific risks to current and future assets which can be managed through a range of adaptation measures. Through the pilot study, CLP Holdings identified a number of situations, which are site specific, but may possibly be applied generally to a wide range of facilities. For example, the company found that the availability of historical data and climate projections varies across Asia. The incomplete information sometimes makes decision-making based on quality data difficult and the robustness of the assessments could be compromised. In light of this, scenario analysis is helpful for determining the "what-if" impacts given the inherent uncertainties. It also helps encompass a wider spectrum of factors (engineering, managerial, legal, cost, company's standards).

UK-based electricity transmission and distribution companies, Western Power Distribution and National Grid, have both assessed climate change impacts on weather-related faults and supply interruptions (South West Climate Change Impacts partnership 2010). In the case of National Grid, this has included assessing flood risk using climate change projections for all its substations (see Box 4).

2.3 Research on Adaptation Solutions

Some work has been undertaken by the utilities interviewed to improve understanding of the technological or behavioral solutions that could reduce climate change vulnerability and attached costs and benefits.

For example, a researcher from the Hydro-Québec research institute assessed the avoided hydropower loss due to unproductive reservoir water spills if operating rules are adapted. By incorporating future runoff projections into an optimization model, which calculates weekly operating rules according to simulated runoff, this work found that for one hydroelectric plant in Québec (Chute-des-passes) (Silver and Roy 2010):

- Annual mean hydropower generation could decrease by up to 14 % if operating rules are not adapted between the control period and 2050; and
- Adapting operating rules could increase hydropower generation between 1 and 15 % in the same period.

Utility interest in distribution loss reduction technologies has increased in recent years. BC Hydro (ex BC Transmission Corporation) is testing the benefits of Dynamic Thermal Rating Systems to operate electricity distribution equipment closer to their design limits, taking into consideration *observed* weather conditions rather than *static* (or normalized) climate data (Janos and Gurney 2008).

3 Early Adaptation Efforts in the Electricity Sector

Adaptation to future climate risks in the electricity sector can take three principal forms:

- Behavioral, whereby utilities relocate their assets, or modify their emergency, maintenance and operating plans;
- Institutional, whereby utilities and regulators adopt climate change adaptation strategies, assign staff responsibility, incorporate climate risk management into existing systems and standards, or disclose information on climate change impacts and adaptation; and
- Technological, whereby utilities invest in new or adapted technologies, or improve the design of assets.

Table 4 presents some generic examples of each of these three types of adaptation actions.

Climate change adaptation being at its very early stages in the electricity sector, there are only few examples of electricity utilities, regulator or industry associations that are taking technological, behavioral, or institutional actions to manage future climate risks.

3.1 Behavioral and Institutional Responses

Behavioral and institutional responses to a changing climate in the electricity sector are limited, though the following real-life examples show leading efforts from utilities.

The integrated UK gas company, BG Group, which operates thermal power plants across the world, has a climate change adaptation strategy in place which requires that staff assess the risks to operations from foreseeable environmental changes arising from climate change.[7] BG Group has designed a Climate Risk Management Framework to support assets and projects in delivering against this requirement. E.ON also has a comprehensive climate change adaptation strategy in place, as explained in Box 5. Other utilities are in the process of developing strategies, for example Eskom and BC Hydro.

To comply with a directive issued by the Department for Environment, Food, and Rural Affairs under the 2008 Climate Change Act, the UK's National Grid published its first Climate Change Adaptation report in 2011, disclosing how the organization has embedded its climate change policy in its risk management procedure, assessed future climate risks, and identified adaptation measures (see Box 4).

To increase resilience against a possible increase in extreme weather events, such as storms and flooding, several utilities, and regulators have invested in climate change adaptation. For example, Entergy in the southeast USA has relocated some of its data centers away from flood risk areas (U.S. Department of Energy 2010). National Grid is investing in flood mitigation work to raise the standard of protection of its substations from a 1:100-year to a 1:1,000-year fluvial or tidal flood event (see Box 4). Recognizing that a changing climate affects weather risk, the Independent Electricity System Operator (IESO) is auditing and assessing the adequacy of existing processes and standards at the local, regional and North American level, to evaluate and manage high-impact, low-frequency weather-related events (Ontario 2011).

Some utilities have also started to recognize that changing the way they operate their assets can reduce vulnerability to future climate change, and is often more

[7] See http://www.bg-group.com/sustainability09/climate_change/Pages/climate_change_our_strategy.aspx (accessed 16/10/2011).

Table 4 Generic examples of adaptation responses in the electricity sector

Electricity sector value chain	Technological		Behavioral			Institutional
	"Hard" (structural)	"Soft" (technology and design)	Re(location)	Anticipation	Operation and maintenance	
Supply						Adopt a corporate- or business-level climate change adaptation strategy Review internal codes of practice and manuals
Thermal power plants	Improve robustness of installations to withstand storms (offshore), and flooding/drought (inland)	Replace water cooling systems with air cooling, dry cooling, or recirculating systems Improve design of gas turbines (inlet guide vanes, inlet air fogging, inlet air filters, compressor blade washing techniques, etc.)	(Re)locate in areas with lower risk of flooding or drought (Re)locate to safer areas, build dikes to contain flooding, reinforce walls and roofs	Emergency planning	Manage on-site drainage and runoff Changes in coal handling due to increased moisture content Adapt regulations so that a higher discharge temperature is allowed Consider water reuse and integration technologies at refineries	
Hydropower	Build de-silting gates and buffers Increase dam height Construct small dams in upper basins Adapt capacity to flow regime	Changes in water reserves and reservoir management Regional integration through transmission connections	(Re)locate based on changes in flow regime		Adapt plant operations to changes in river flow patterns Operational complementarities with other sources (for example natural gas)	
Wind power		Improve design of turbines to withstand higher wind speeds	(Re)locate based on expected changes in wind speeds (Re)locate based on anticipated sea level rise and changes in river flooding			

(continued)

Table 4 (continued)

Electricity sector value chain	Technological		Behavioral			Institutional
	"Hard" (structural)	"Soft" (technology and design)	Re(location)	Anticipation	Operation and maintenance	
Solar power		Improve design of panels to withstand storms	(Re)locate based on expected changes in cloud cover	Repair plans to ensure functioning of distributed solar systems after extreme events		
Transmission and distribution	Improve robustness of infrastructure to withstand more extreme weather events Burying or cable re-rating of the power grid		Emergency planning	Regular inspection of vulnerable infrastructure such as wooden utility poles		
Demand	Invest in high-efficiency infrastructures and equipment Invest in decentralized power generation, such as rooftop PV generators or household geothermal units			Efficient use of energy through good operating practice		
Support or connected infrastructure, and local communities		Consider underground fossil fuel transfers and transport structures				Engage in community forums

Source adapted from Ebinger et al. 2011 cost-effective than making physical changes to existing assets. For instance, Hydro-Tasmania has changed its seasonal operating rules and turbine outage management methods to cope with reduced inflows and changing seasonality (Brewster et al. 2009).

There are a few examples of utilities that have started mainstreaming climate risk management into everyday business. Hydro-Québec considered climate change impacts as part of the Environmental Impact Assessment (EIA) for a new hydropower complex on the La Romaine river in Québec, Canada (see Box 1). Australian utility, ActewAGL, appraised how climate change may affect flood risk as part of its EIA, and elevated electrical equipment in new substations to ensure the integrity of the network during peak flood events (AECOM/Purdon Associates 2009). There is one precedent in Ontario, Canada, whereby the review panel of an Environmental Assessment Report for a new nuclear power plant requested that the project promoter does more in-depth and localized modeling of climate change impacts, based on high resolution data, to ensure adequate consideration of climate change risks before a construction license is issued (Darlington New Nuclear Power Plant Project 2011).

In relation to long-term resource planning, utilities surveyed have started to discuss possible exemptions or differential prices with government and regulators to improve their capacity to cope with climate change or to cover adaptation costs. For instance, during the summer 2003 European heat wave, Electricité de France negotiated exemptions on maximum water discharge temperature obligations, to avoid shutting down too many nuclear plants. An exceptional exemption from these legal requirements was granted to four conventional thermal power plants and sixteen nuclear reactors, permitting them to exceed the maximum discharge water temperature (Letard 2004). Hydro-Québec has integrated the effects of warming into its future demand load forecasts presented to the Québec regulator (see Box 1).

Finally, a handful of professional bodies (e.g., the Canadian Electricity Association) have also recognized that climate change poses a risk to the electricity industry, and are supporting initiatives that help to better understanding climate risks and how to reduce vulnerability.

Box 3. Eskom

Eskom was established in South Africa in 1923 as the Electricity Supply Commission. In July 2002, it was converted into a public limited liability company, wholly owned by the government. Eskom is one of the top 20 utilities in the world by generation capacity, with a net maximum self-generated capacity of 41,194 MW.

Eskom is the largest electricity generation, transmission and distribution company in Africa. It generates approximately 95 and 45 % of the electricity used in South Africa and the whole African continent, respectively. It buys and sells electricity in the countries of the Southern African Development

Community (SADC). Eskom operates coal- and gas-fired power stations, nuclear plants, hydropower facilities, and wind turbine sites. In 2011, the company looked after 28,000 and 46,000 km of high and low-voltage electric lines respectively.

Eskom's Climate Change Response

Eskom supports South Africa's government approach of contributing to global efforts to combat climate change whilst ensuring the sustainability of its economy and society. South Africa is a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, and has been leading a number of global and regional initiatives which promote sustainable responses to climate change adaptation. The National Climate Change Response Policy Development process has been initiated by the Department of Environmental Affairs (DEA). This has included the development of the National Climate Change Response (NCCR) White Paper for South Africa approved by the South African Cabinet in October 2011.

The NCCR has highlighted the following objectives for South Africa on climate change:

- Make a fair contribution to the global effort to stabilize greenhouse gas concentrations (i.e., mitigation of climate change); and
- Effectively manage unavoidable climate change impacts through interventions that build and sustain South Africa's social, economic, and environmental resilience and emergency response capacity (i.e., climate change adaptation).

Eskom supports this approach in the form of its corporate Climate Change Response Strategy which highlights Eskom's commitment to deal with climate change in the following six key areas:

- Diversification of the generation mix to lower carbon emitting technologies;
- Energy efficiency measures to reduce demand and greenhouse gas and other emissions;
- Innovation through research, demonstration, and development;
- Adaptation to the negative and positive impacts of climate change;
- Investment through carbon market mechanisms; and
- Progress through advocacy, partnerships, and collaboration.

In the financial year 2010 to 2011, Eskom reviewed its Climate Change Response Strategy, with a view to better address the company's resilience to climate variability and long-term changes in climate.

Eskom's research to understand changes in climate, future impacts, and adaptation

The Climate Change and Sustainability Department in partnership with various business units within Eskom has been hosting a number of applied research, workshops, and conducting surveys to feed into the process of developing Eskom's adaptation strategy. This work includes the following:

- Definition of climate change impacts for South Africa and its specific impacts on Eskom;
- Investment in applied climate change research;
- Redefinition, benchmarking and continuous review of business planning assumptions and continuously review;
- Cost-benefit analysis of adaptation interventions (adaptation costs curves);
- Integrated risk and resilience management (including the identification of climate-related thresholds in business systems, unacceptable levels of climate-related risk, and required levels of adaptive capacity and business resilience); and
- Integration of climate change adaptation imperatives into business operations.

By 2011, Eskom had done research in two separate areas, as explained below:

(a) Case studies on weather impacts

In order to understand vulnerability to changes in climate, the company analyzed historical and current weather conditions, extreme events and climate variability, and their impacts on a number of business areas, including two coal-fired power stations (Hendrina and Kendal), the NorthEast transmission grid and the Eastern region distribution.

(b) Weather surveys

Eskom has also undertaken weather surveys asking the different Eskom businesses the following key questions:

- What weather data is Eskom already monitoring across all operating units and strategic functions?
- Which business processes and operations are affected by weather phenomena and will benefit from appropriate weather data integration?
- What aspects of weather do we need to monitor in real-time to warn about extreme weather events for situational awareness and response purposes in the control rooms and customer nerve centers?
- What aspects of weather data do we need to have in a long-term climate data warehouse for research and analysis purposes?

Results from these surveys have been assessed and have also informed Eskom's support in long-term research activities and strategies relevant to climate change resilience.

(c) Thresholds, adaptive capacity and vulnerability assessments of Eskom systems

Eskom is currently investing in research to further define climate-related thresholds, as well as the vulnerability and adaptive capacity of its systems to future climate change impacts. These studies are undertaken in collaboration with the University of Cape Town (UCT), the University of Kwazulu-Natal (UKZN), and the Council for Scientific and Industrial Research (CSIR). They include the following activities:

- Identifying climate-sensitive thresholds of vulnerable systems within Eskom, possible adaptation measures, and associated costs and benefits;
- Developing climate change projections for rainfall, temperature, lightning and storms;
- Assessing the impacts of climate change on water resources in the Waterberg area;
- Modeling the hydrology of four catchments in the Waterberg area and around the Hartebeespoort pipeline; and
- Modeling of summer convection (thunderstorms, lightning and rainfall intensity and frequency) over Southern Africa (Table 5).

Promote dry cooling systems to reduce reliance on freshwater for thermo-electric or nuclear power plant cooling
Although the company has started investing in dry cooling in the mid-1980s, Eskom identifies dry cooling systems as a short-term climate change adaptation measure for new power stations in its "Climate Change Commitment" (Eskom 2009). Eskom recognizes that dry cooling involves higher costs at the construction and operation stages, reduced overall plant efficiency, and lower plant output. Eskom accepts that sustainability and adaptation will override economic considerations in certain cases when choosing between wet or dry cooling.

In 2000, Eskom operated the largest power plants with a dry cooling system in the world (Matimba, Kendal, and Majuba). Eskom's investment in dry cooling has resulted in an estimated combined saving in excess of 90 million cubic meters of water per annum (Pather 2004).

3.2 Technological Responses

Only a few utilities have begun to implement technological responses to climate change adaptation, by making structural changes to existing assets (e.g., increasing energy efficiency of electrical equipment), building new assets (e.g., building a

Table 5 Results from Eskom case studies on weather impacts for four assets

Assets	Vulnerability and levels of adaptive capacity	Existing and potential adaptation to climate change measures
Hendrina Power Station	*A: Increased heavy rainfall and wet coal* Heavy rain causes wet coal which has the following impacts: – Blockages in bunkers – Clogging of milling plant – Reduction in the amount of electricity generated if load losses result	– Coal blending – Reclaim the coal – Use of sensors and redirecting wet coal back to the stockpile. However, this causes uncertainty when it stays wet for a prolonged period
	B: Increased heavy rainfall and dams overflow (normal and ash) – Increased water levels may result in bursting of the dams. Overflows yes, but how possible is actual "bursting" of dam walls?	– Increase the dam capacity – Build additional dams – Change dam management strategy – Drainage pipes – Reuse more water (treating water)—also impacts on other sustainability issues and should be a priority
	Floods – Ash dams overflow	– Build new dams – Replace the dam lines – Increase the frequencies of dam level inspections
	Low temperature – Delayed combustion process resulting in load losses due to boiler losses	– Use of more coal to get the same MW output, but at high cost
	High temperature – Increased condenser and vacuum temperatures	– Use of more coal to get the same MW output—at high cost
	Lightning – Stack pollution monitors	– Use lightning arrestors

(continued)

Table 5 (continued)

Assets	Vulnerability and levels of adaptive capacity	Existing and potential adaptation to climate change measures
Kendal Power Station	*Heavy rainfall* Wet coal results in the following impacts: – Blockages in bunkers – Clogging of milling plant – Reduction in the amount of electricity generated	– Coal blending – Reclaim the coal – Use of sensors and redirecting wet coal back to the stockpile – Cover the coal stockpile
	Drought Station runs out of recycled (potable) water from the three dams	– Station uses water from reservoirs pumped from Vaal River which is dirty and expensive to clean
	High temperature – Air heater packs affected on the units, resulting in high particulate emissions (especially during summer) – Affects the performance of the cooling tower (if dirty) – Heat exchanges on the Auxiliary cooling plant are affected resulting in potential multiple-unit trips – Increased condenser and vacuum temperatures – Load losses above certain temperature because of drop in efficiency	– Replace the design layers that were removed – Apply for exemptions to obtain waiver under license to operate (for the high emissions) – Use more coal to get the same output—at high cost
	Low temperature – Delayed combustion process, load losses due to boiler losses	– Use of more coal to get the same output—at a high cost
North East Transmission Grid	*Heavy rainfall* – Excessive vegetation growth on the transmission line servitudes, interfering with the lines' clearance and may cause fires resulting in line faults – Submerged tower footing and resultant rusting of structures	– Increase the frequency of cutting the grass, i.e., cutting the grass three times a year instead of twice – Use stainless steel material to reduce corrosion – Build foundations as per the design specifications
	Ice/mist and fog – Ice/mist or fog covers insulator sheds in the presence of pollution, causing flashovers on the substation transformers and lines resulting in tripping	– Coat the insulators with silicone – Use water-repellent composite polymer insulators—expensive – Increase spacing of insulator sheds – Install shed extenders – Pollution deposits on the insulators
	High temperature – Conductor sagging which may cause fires	– Contact national control to switch off the affected line, until the fires are extinguished – Send fire-fighters to the site to extinguish the fire – Carry out planned and controlled burning

(continued)

Table 5 (continued)

Assets	Vulnerability and levels of adaptive capacity	Existing and potential adaptation to climate change measures
Eastern Region Distribution	*Heavy rainfall* – Damage to insulators, transformers, surge arresters and circuit breakers	– Use special type of insulator – Coat insulators with a special silicone grease – Use silicon rubber coating – Use steel instead of wooden poles
	Ice/mist – Damage to lines and substations	– Use shells of different diameters to avoid accumulation of ice to reduce the flashovers – Increase the distance between insulators – Use cranes, helicopters and vehicles to displace the snow/ice
	– Conductor sagging which may cause fires	– Increase the height of tower—increasing the clearance distance between the rower and vegetation – Reduce the spans if the highest tower is used already – Increase the tension of the conductors
	Floods – Substations and lines inland are affected by floods – Foundations of towers are damaged resulting in their collapse	– Increase the elevation of the substations
	Sea swells – Traction substations that supply railway lines are impacted	– Increase the distance between the coast and the substations

dam in upper basins to regulate future runoff increase), or modifying asset design (e.g., improving the design of transmission pylons to withstand higher ice or snow loads).

Hydro-Tasmania's *Climate Change Response Strategy* includes a number of technological adaptation measures aimed at compensating part of the projected future loss of inflows, such as:

- Increasing water storage capacity to capture higher inflows during winter and release water during drier periods;
- Replacing the coating of existing water canals (also known as "relining") and increasing the capacity of a few water canals to reduce evaporation and increase inflow efficiency;
- Confirming that existing weirs are operating efficiently to ensure that water flows are well-regulated, and considering new water diversion schemes that could pass more water through existing hydropower plants; and
- Developing new projects to make up for the expected loss of output, such as mini-hydro schemes or refurbishing old power stations (Brewster et al. 2009).

These adaptation measures could increase production capacity by over 1,000 GWh, at a total cost of approximately AU$420 million. Building new small hydropower plants, increasing storage capacity, and building new dams are expected to have a significant cost (AU$320 million), with a generation potential of 700 GWh (Brewster et al. 2009). Conversely, Hydro-Tasmania has identified measures that are relatively low-cost, but have a considerable generation potential: for example, raising dam height and upgrading water canals would cost AU$48 and AU$10 million respectively, with a corresponding total generation potential of 300 GWh (Brewster et al. 2009).

Since the 1980s, South African utility Eskom has made considerable investments in dry cooling systems: the company has increased its air-cooled thermoelectric generation capacity by 10,000 MW between the mid-1980s and the early 2000s (Lennon 2010) Fig. 3. Eskom has identified this as an adaptation measure to cope with future reduced cooling water availability in South Africa (see Box 3).

Finally, there are a few tangible technological investments in transmission and distribution. Following the 1998 Eastern Canada ice storm, which cost Hydro-Québec CDN$ 725 million in damages,[8] the utility reviewed its design standards for high voltage lines. An internal technical committee recommended an increase in maximum ice and hourly wind loads, and cumulative ice/wind loads, on transmission hardware, and the installation of special pylons at standard intervals to avoid cascades of falling pylons during high ice load events.[9] The Québec utility

[8] Extreme icing damaged 116 transmission lines and 3,110 support structures (including 1,000 steel pylons), as well as 350 low-voltage lines and 16,000 wood posts. To restore service rapidly to its customers following the disaster, Hydro-Québec spent CDN$725 million repairing the lines and support structures with the least damage and building temporary transmission and distribution equipment. See Turcotte et al., 2008, ibid.

[9] René Roy, Hydro-Québec, personal communication, 25/10/2011.

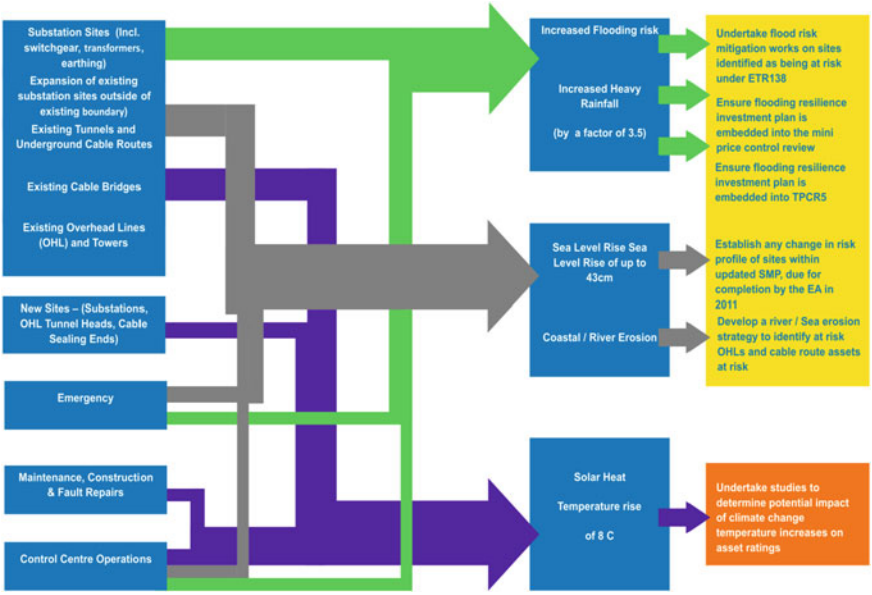

Fig. 3 Actions (on the *right*) in response to climate change risks identified (on the *left*). Source National Grid

spent close to CDN$ 1 billion between 1998 and 2008 replacing old pylons and structures with stronger ones (Turcotte 2008). The utility was planning to spend CDN$200 million by 2012 on the electricity system interconnection between the Canadian provinces of Québec and Ontario and on anti-icing equipment, which are expected to reduce vulnerability to future extreme winter weather events (Turcotte 2008). BC Hydro is testing high performance corrosion-resistant materials. For example, it has installed cross arms made of high performance composite material, which have much longer lifetimes and higher resistance to extreme weather conditions (Toth 2011). The utility has also started replacing wooden electricity poles, damaged by mountain pine beetle infestations[10] with metal ones, and is testing Dynamic Thermal Rating Systems to improve the capacity of its transmission system. In Australia, the Victorian Bushfires Royal Commission recommended burying electric lines to reduce the risk of network failures due to damage during extreme weather events and wildfires (Linnenluecke et al. 2011).

[10] Climate change has exacerbated recent mountain pine beetle outbreaks in Western North America. Unusually hot and dry summers (favorable for beetle reproduction), and mild winters (which allow beetle larvae to survive), have contributed to infestations destroying more than 700 million m3 of pine in British Columbia, Canada, which represents more than 50 % of the province's pine. See Carroll et al. 2003.

3.3 Adaptation Investment Estimates

Though uncertainty remains about the exact cost of future climate change impacts, the weather-related costs suffered by some electric utilities in the recent past provides a glimpse of the potential magnitude of future climate change challenges for the electricity sector. For example, Hydro-Québec spent US$679 million in emergency measures and repairs after a destructive ice storm in 1998 to restore service to customers (Turcotte 2008).

Interviews with electricity utilities operating in different geographical areas and markets show a wide range of capital expenditures being allocated to manage climate change impacts. This brief survey of five utilities accounted a cumulative total of approximately US$ 1.5 billion worth of allocated and planned expenditures for climate change adaptation. This is a modest figure compared to the magnitude of the expected risks and opportunities they aim to address, such as repair costs following a single extreme weather event, loss of hydropower output due to reduced inflows or reduced cooling water availability. Climate change damage cost estimates for the power sector could reach US$ 1.9 billion per year globally for the 2010–2050 time period, provided the world remains on a 2 °C global average warming trajectory by 2050 (World Bank 2010). As such, it is likely that the benefit to cost ratio of climate change adaptation investments in the electricity sector is attractive. This suggests that there could be a strong business case to scale up such investments in the electricity sector.

Box 4. National Grid

National Grid owns and operates the high voltage electricity transmission system in England, Wales and operates the power transmission system in Scotland. It also owns the UK's gas transmission network and four of the eight gas distribution networks. In addition National Grid owns and operates electricity assets in New England and New York.

National Grid is at a "very advanced" stage of embedding climate change adaptation into its systems and everyday operations. Responsibility for climate change risk management is distributed throughout the organization.

Following the introduction of the UK Climate Change Act 2008 and a directive to report in March 2010, National Grid was required by law to present a climate change adaptation report to the Department for Energy, Flood, and Rural Affairs. The National Grid Electricity Transmission Climate Change Adaptation Report is the culmination of the first phase of adaptation reporting (National Grid Electricity Transmission plc 2010). National Grid also produced a separate report for its gas businesses in the UK.

In its Climate Change Adaptation Report, National Grid presents the result of its enterprise-wide climate risk assessment and adaptation identification work (Fig. 3). The extreme scenarios of the official UK Climate

Projections of 2009 (UKCIP09) were used to allow for a "worst case scenario," in association with specific electricity transmission characteristics. The report suggested that National Grid's assets and procedures are generally "resilient to climate change that is projected to occur" up to 2080. Where they exist, risks are localized and do not threaten loss of supply on a large scale. See Table 6 for a summary of climate impact and risk studies carried out by National Grid.

National Grid's risk process has found that there is currently little justification to support adjusting network or asset design standards except for the areas of flooding, and potentially the thermal ratings of equipment and apparatus (see below for more details on flood risk and thermal ratings), although factors other than climate change dominate the latter.

In order to address climate change, National Grid's risk register has been updated in response to specific risks. Actions with associated timelines have been formulated to address the identified risks. It acknowledges that climate risk management must be flexible to accommodate new information when it comes to light. An example may be the development of more accurate climate change projections for the UK. As such National Grid's risk process is "constantly reviewed and updated with appropriate actions and targets."

Flood resilience

National Grid considers that flooding is an important climate change issue that could cause considerable risks to its businesses. Following severe flood events in the UK during the summer of 2007, an industry Engineering Technical Report (ETR 138) was developed setting out a common approach to the assessment of flood risk. The task group that produced ETR 138 was made up of representatives from networks companies (including National Grid), the UK Department of Energy and Climate Change (DECC), the UK Office of Gas and Electricity Markets (OFGEM), the UK Environment Agency (EA), the Scottish Environment Protection Agency (SEPA), the UK Meteorological Office (Met Office), and the Pitt Review Team. Since then, power transmission companies have agreed to protect the grid and primary substations against flooding by 2022. As part of this process, flood risk assessments explicitly integrate the impact of climate change (i.e., changes in precipitation regimes and sea level rise) on the delineation of flood zones.

National Grid has begun flood mitigation work at all its substations at risk of a 1:100 year fluvial or tidal flood event taking into consideration projected climate change. Until work to defend sites is complete, National Grid has emergency plans to utilize a 1.7 km mobile flood defense system, which can be deployed at short notice. In addition, new substation designs take into account projected flood risks and include design features such as placing critical plant and equipment in elevated positions, for example on "stilts." The costs of flood management schemes will be highlighted as part of

Table 6 Ongoing and past National Grid climate change impact studies

Projects with climate change considerations		
Project title	External body	Energy participants
Vegetation management	ADAS	National grid, EDF, SP, ENW, CN
Pluvial flood risk modeling	ADAS	CN
Future network resilience	Met office	ENA
Dynamic ratings project	Met office	CN
EP1/2 impact of climate change on the UK energy industry	Met office	ENA
Urban heat Island study	Birmingham university	CN
Earthing information systems	BGS and NSA	EDF, CN
Flooding risk reduction	Mott McDonald	National grid
Investigation to network resilience to weather events	EA, Met office	ENA
Reappraisal of seasons and temperature thresholds for the power rating of electrical plant—a pilot study considering transformers only 2006	Met office/Southampton dielectric consultants ltd	National grid
Reappraisal of seasons and temperature thresholds for the power rating of electrical plant—a pilot study considering transformers only 2007	Met Office/Southampton dielectric consultants ltd	National grid
Reappraisal of seasons and temperature thresholds for the power rating of electrical plant—a pilot study additional work 2008	Met office/Southampton dielectric consultants ltd	National grid
Flooding risk and severe weather mitigation demountable flood barrier facilitating work	N/A	National grid
Flood risk assessment	N/A	National grid
Flood risk mitigation works 1:100 risk sites	N/A	National grid
Flood risk mitigation studies 1:200 risk sites	N/A	National grid
Flood risk mitigation studies 1:1000 risk sites	N/A	National grid
Flood risk mitigation, towers and erosion studies	N/A	National grid

Source National grid

upcoming customer tariff negotiations with Ofgem (the UK energy sector regulator).

Transmission and distribution equipment ratings

The current thermal rating of electrical equipment is dependent on operating ambient temperature. It defines the maximum electrical current which can be passed safely without overheating (potentially leading to sagging of lines and breaching of clearance limits). If ambient temperature increases, the maximum current rating of overhead lines, cables, transformers, and switchgear is reduced. This restricts the transmission capacity of an electricity system.

Table 7 shows the range of percentage de-ratings across the UK for typical transmission and distribution line types based on UKCP09 projections (note that National Grid only has responsibility for the transmission system). The maximum percentage de-rating for transmission overhead lines in the UK is

Table 7 Reduction in asset capacity as a result of projected changes in temperature

EP2—Typical Reduction in asset capacity for high emissions at 90 % Probability Level	
Equipment	UKCP09 Period 2070–2099 (%)
Overhead lines	3
Underground cables	5
Transformers	5

Source National grid

only 3 %, which is not expected to considerably affect operating costs and tariffs. However, in places where equipment is already operating close to its design range, for example in areas that currently experience extremely hot temperatures, this could cause non-negligible reductions in transmission capacity. Further, in developing countries where supply is already insufficient, a 3 % reduction in current rating could be significant.

In theory, reduced current rating could justify to re-conductoring some overhead lines, but, in practice, other concerns have priority (e.g., satisfying customer demand). For instance, growth of electricity demand in the UK is anticipated to be 0.2 % yearly until 2016–2017 (1.4 % in the high growth scenario). The associated required transmission network upgrade exceeds by far the improvements required to accommodate reduced current rating (Table 7).

National Grid suggests that "additional work is needed to study the potential impact of reduced ratings in order to ascertain potential effects on the system and associated costs." As de-rating is a function of demand and peak temperatures, National Grid is also investigating the use of real-time rating monitoring and management to increase the capacity of overhead lines and reduce the need for reconductoring.

4 Current Focus of Adaptation Efforts and Gaps

Electricity sector climate change research and adaptation efforts seem to have concentrated thus far on a handful of issues (see Tables 8 and 9). Further, there are a number of adaptation responses which could be promoted in the electricity sector at no or low additional cost. These are discussed below.

4.1 Hydropower Output

Generation of hydroelectricity is very vulnerable to climate change, because it relies directly on the climatically sensitive hydrological cycle.

Table 8 Electricity sector risks comprehensively assessed by the electricity industry

Electricity sector value chain	Climate risks	Industry examples of risk assessment
Resource endowment		
Hydropower	Runoff	Hydro-Québec, BC Hydro, Hydro-Tasmania
Wind power	Wind field characteristics, changes in wind resource	BC Hydro
Solar power	Atmospheric transmissivity	
Wave and tidal energy	Ocean climate	
Supply		
Thermal power plants	Generation cycle efficiency, cooling water availability, increased frequency of extreme events, sea level rise	E.ON, Eskom, CLP Holdings
Hydropower	Water inflows and seasonality	Hydro-Québec, BC Hydro, Hydro-Tasmania
Wind power	Alteration in wind speed frequency distribution	
Solar power	Reduced solar cell efficiency	
Transmission and distribution	Increased frequency of extreme events, sea level rise	National Grid, Hydro-Québec, ActewAGL, BC Hydro, Western Power Distribution
Demand	Increased demand for indoor cooling, reduced heating requirements	Hydro-Québec, Electricité de France, Canadian Independent Electricity Operator
Support or connected infrastructure, and local communities	Increased frequency of extreme events, sea level rise	Eskom, Entergy

Source authors, and adapted from Ebinger et al. 2011

Table 9 Examples of adaptation responses that have been implemented by surveyed electricity utilities

Electricity sector value chain	Adaptation responses implemented by electricity utilities or regulators
Supply	
Thermal power plants	Eskom, E.ON, CLP Holdings, Entergy, EDF, BG Group
Hydropower	Hydro-Québec, Hydro-Tasmania
Wind power	
Solar power	
Transmission and distribution	Hydro-Québec, UK National Grid, ActewAGL, BC Hydro, western power distribution
Demand	Hydro-Québec
Support or connected infrastructure, and local communities	Entergy

Source authors

As mentioned above, the hydropower sector is the focus of considerable research and adaptation investments. However, reliable methods and tools to appraise and plan for future changes in water inflows due to short- and long-term climate variations are still being developed. Efforts are needed to make sure such work is of value value to utilities in developing countries, where observed hydrometeorological data is often limited.

4.2 Transmission and Distribution Integrity

Extreme weather events—such as snow or ice storms, high winds, and flooding—are widely recognized as key risks for power transmission and distribution. For example, flooding can cause electricity supply interruptions, downtime, and serious infrastructure damage, by wetting electrical equipment in substations, and preventing staff from accessing equipment for maintenance or repair (Grynbaum 2011; National Grid Electricity Transmission plc. 2010; Williamson et al. 2009).

Work is underway in these areas to improve knowledge, and the industry is planning for more extreme weather by adopting stronger design standards, and improving maintenance, monitoring and emergency plans.

However, considerable uncertainties persist around the likelihood and severity of these future extreme hazards. This is partly due to the lack of reliable observed data at short timescales for these variables, and the limited capacity of climate and hydrological models to accurately simulate extreme weather events.

4.3 Efficiency Losses

Higher ambient temperatures and changes in climate variables that contribute to cool electrical equipment (wind, rainfall, and cloudiness) could reduce the current rating of electrical lines and other equipment, as explained in Sect. 3. Technical solutions exist to manage this risk: for example, replacing old equipment with equipment that has a higher thermal rating, or monitoring real-time data to estimate current rating more accurately.[11]

While this poses a challenge to operating conditions, well-designed systems will most likely cope with such efficiency losses. Yet, current business and regulatory environments for electricity utilities impose new demands and constraints on the development, operation, and maintenance of electricity systems. In this context, even small efficiency losses could affect overall power system efficiency objectives. Furthermore, in the case of systems operating close to their design

[11] Similarly, higher ambient temperatures will reduce the heat rate and power output of natural gas-based generating units. See Ebinger and Vergara 2011.

ranges, for example in areas that currently experience extremely hot temperatures, higher temperatures could jeopardize critical design thresholds and lead to unacceptable efficiency ratios.

4.4 Demand Load Forecasts

Short-term electricity demand depends on the time of day and weather conditions. Research indicates that climate change will also have an influence on long-term demand (Wilbanks et al. 2007; ESPON 2010). As such, rising temperatures should be a consideration in demand load forecasting and long-term investment plans.[12] The technical summit organized by the Electric Power Research Institute, the North American Electric Reliability Corporation, and the Power System Engineering Research Centre on this issue can be taken as evidence that this is seen as an industry-wide risk (EPRI et al. 2008).

A few utilities have started working on this, as shown in Sects. 2 and 3, but more collaboration between the industry and hydrometeorological institutes will be needed to agree on ways to revise long-term forecasting methods and take into account the warming trend and its effects on baseline and peak power demand loads.

4.5 Gaps in Research on Climate Risks

Table 8 shows that most electricity utilities have focused their attention on a handful of risk issues and that there are a number of risks which have not yet been comprehensively assessed by the industry.

For instance, efforts to understand how a changing climate will affect renewable electricity generation have largely concentrated on hydropower. This is not surprising considering that hydropower represented more than 80 % of the total installed capacity for renewable electricity worldwide in 2008. However, non-hydro renewable electricity has increased considerably in recent years, and it is expected that this trend will continue into the future (International Energy Agency (IEA) 2011).

Limited attention has been paid to indirect climate change risks, which arise through impacts on support or connected infrastructure (e.g., transport networks) or impacts on local communities. For example, disruptions suffered by customers during extreme weather events lead to reduced demand and sales for electricity

[12] Due to warming, less heating will be needed for industrial, commercial, and residential buildings and cooling demand will increase, though this will vary by region and season. However, overall net energy demand is influenced for the most part by the economy and the structure of the energy industry. See Wilbanks et al. 2007.

utilities. CLP Holdings and Entergy have recognized that indirect risks could, in some cases, be more important to utilities than direct climate change effects on assets or operations.

Box 5. E.ON

E.ON, a global electricity supply company, has spent resources to understand and manage the future impacts of climate change on its operations for almost 10 years. Key activities taken to date by E.ON to manage climate risks in the United Kingdom are described in Table 10 below.

E.ON's assessment of climate change impacts on its UK generation business
E.ON designed a consequence/likelihood risk assessment process to determine the overall degree of risk from climate change at each of it sites. Over 150 individual risks were identified during the risk assessment process. These were used to generate a list of key climate change impacts. Figure 4 plots the key current and future climate change risk onto E.ON's consequence versus likelihood matrix.

Conclusions
Overall, climate change represents a low risk to E.ON's power generation business, for a number of key reasons:

- A relatively small change in climate is projected during the lifetime of existing assets;
- The diverse design and geographical locations of its power station fleet reduces the overall risk; and
- The inherent flexibility of each station enables short-term responses to climatic pressures.

The most significant risks identified relate to drought and high ambient temperature. E.ON's climate change adaptation plan contains a number of key actions, to:

- Reduce uncertainty in future drought risk assessment, site flood risk assessments, and the interaction between the E.ON climate change plan and the plans of its stakeholders; and
- Improve internal management systems, by (1) developing and regularly updating a climate change projection fact sheet; (2) assessing E.ON's consideration of climate change adaptation during the development of new power stations; and (3) enhancing E.ON's risk-based asset management framework to incorporate ongoing assessment and monitoring of climate change risks.

Table 10 Timeline of climate change adaptation research undertaken by E.ON

Study details	Utilization for E.ON	Date
Climate change impacts tracking activities	Informing E.ON UK of developments	2002–2007
Analysis of data in UK climate impacts programme (UKCIP)02	Informing E.ON UK of developments	2002
Participation in scoping study (known as EP1) on the impacts of climate change on the UK energy industry (joint venture with met office)	Highlights significance of climate change impacts for electricity generation sector	2006
Analysis of EP1 conclusions	Initial investigation of EP1 results for E.ON UK generation	2006
Assessment of external research programme building knowledge for a changing climate (BKCC): impacts of climate change on the built environment	Identifying relevance to E.ON UK	2007
The impact of climate change on the UK energy industry (joint venture) with Met Office—EP2 participation and analysis	Sector-wide identification of general impacts of climate change	2008
Climate change risks to generation plant—identification of main issues	Scoping study for E.ON UK generation	2008
The impacts of climate change on thermal power stations: a user requirement study. A study in collaboration with Met Office	Climate variable data source analysis	2008
Developments in CCA policy	Assessment of UK CCA policy and outline of E.ON UK CCA plan	2009
Analysis of UKCIP09 UK climate projections accessibility of data—review of usefulness to E.ON UK	Assessment of data pool; basic processing tools	2009
Project to produce methodology for climate change impact assessment for E.ON UK generation assets	To enable CCA report for E.ON UK generation to be produced to meet requirements placed on reporting authorities	2009–2011

Source E.ON

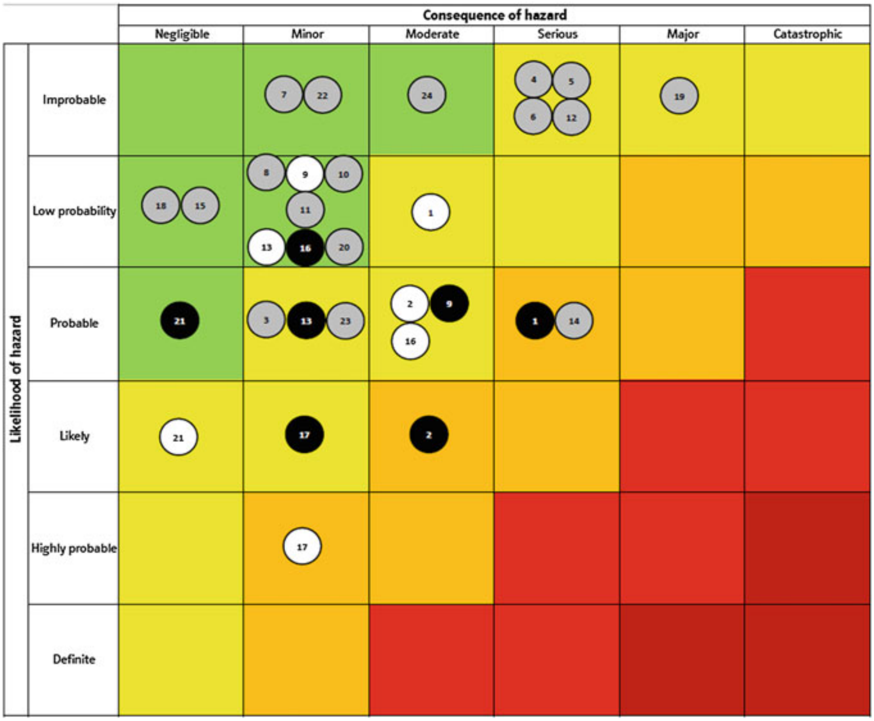

Fig. 4 Matrix of key current and future climate change risks. *Source* E.ON

Key
◯ Current risk
● Future risk
◯ Current and future risk (where the future risk is not predicted to move into a different risk band)

1 Low river flow impact on station cooling/operation
2 Low river flow impact on compliance
3 Restricted supply of towns water
4 Extreme high river water levels
5 Coastal flooding
6 Flooding within site boundary
7 Impact on oil interceptors
8 Debris at water inlet
9 Impact on water quality
10 Impact on critical commodity access
11 Impact on staff access
12 High ambient temperature causing station trip
13 High air/water temperature impact on compliance
14 High temperature impact on performance
15 High temperature impact on occupational health
16 Freezing of water-containing equipment
17 Anti-icing impact on performance
18 Low temperature impact upon compliance
19 Impact on Operator safety
20 Impact of access of critical commodities
21 Impact on access of staff
22 Lightning
23 Meteorological conditions leading to cooling tower visible plume grounding
24 Subsidence/landslide

4.6 Gaps in Adaptation Action

As shown in Table 9, adaptation responses in the electricity sector remain patchy. More effort has been made in managing climate risks for transmission and distribution than for generation or demand. This is probably due to the fact that weather risk management is written in the DNA of the transmission and distribution industry, and climate change adaptation measures have often been taken following an extreme weather hazard.

Surprisingly, despite considerable industry research on climate change risks for hydropower output and demand loads, there is little evidence of technological adaptation responses in these areas, except for Hydro-Tasmania and Hydro-Québec. This is perhaps explained by the fact that water variability is an intrinsic component of hydropower equipment design and operation, and by the fact that there may be too much uncertainty to justify costly capital investments. This is why electricity producers, such as Hydro-Québec, prefer adapting their environmental impact management systems and operating rules.

Investments in technological adaptation measures remain limited to a few examples (for example, Dynamic Thermal Rating Systems, dry cooling and stronger design standards for transmission hardware), though in many cases they are primarily justified by considerations other than climate risks.

Electric utilities that are ahead of their peers on their "climate change adaptation journey" have started adopting climate change adaptation strategies and disclosing their actions to investors and stakeholders, as is the case for Eskom (see Box 3), E.ON (see Box 5), National Grid (see Box 4), and BG Group.

5 Lessons Learnt and Ways Forward

This stock-taking exercise helps point toward some research and adaptation gaps that would need to be filled to improve the climate change of electricity systems.

5.1 Quality and Tailored Climate Data and Information

Electricity organizations need accessible and high-quality data and information on observed and future climate conditions that are tailored to their needs, so they can plan ahead effectively. Data is required in a range of:

- Timescales, from short-term data for better management of existing supply/demand balance, through to data several years or decades ahead for planning and designing new energy assets;
- Spatial resolutions, from site specific to region- and country-wide; and

- Statistical variables other than averages (e.g., maximum consecutive days with no rain) and derived variables (e.g., Heating Degree Days), which are not directly given by climate models.

The current problem is that hydroclimate observations and future projections are not immediately available in a format that is easily adapted to electricity sector decisions (Troccoli 2009). For instance, utilities may require rainfall information at a high spatial resolution (e.g., a couple of square kilometers), and on short timescales (e.g., 12 h or daily), to assess future flood risk, but this is not immediately available from climate model projections. Furthermore, there is high model uncertainty about future changes in specific variables that are critical to electricity sector decision makers, such as rainfall, runoff, and wind. This leads to a "wait-and-see" attitude among most utilities which constrains climate risk management action.

It appears increasingly important for the electricity sector to work closely with hydrometeorological offices and research institutions to understand what data are available, and to identify gaps. The electricity sector can lobby government to fill these data gaps, in order to respond to industry needs. An example of successful collaboration on data development is provided by Hydro-Québec and Ouranos in Canada.

5.2 Operational Information on Impacts, Risks and Adaptation Strategies

A lot of the information available on climate change impacts and adaptation is often too *high-level* to be applied *operationally* within the electricity sector. For example, there are a number of resources explaining potential industry impacts and adaptation measures, without assessing the specific risk for the industry or explaining the methods, technological innovations, or cost-benefit ratios of different adaptation solutions. They are useful for establishing a holistic understanding of the challenges for the industry at a global, regional, or country level, and for building the case for climate change adaptation in the industry. However, examples of *applied* work influencing changes in planning, risk management, design, or operations, are limited.

A few utilities are doing work to assess a number of climate change risks and to identify cost-efficient adaptation measures. However, considerable uncertainties remain on the future likelihood and severity of different climate-related impacts. There is no clear view on *which* impacts will constitute material risks for power generation, transmission, and distribution, *when* these risks are likely to be felt, and *where* electricity assets or operations will most exposed.

Furthermore, findings from preliminary research efforts cannot easily be transferred to other utilities or locations. This is because the way a changing climate affects an electricity system will depend on a number of factors:

- The electricity system characteristics (e.g., asset design standards and operating rules);
- The exposure to climate and hydrometeorological variables and hazards, which depends on location (e.g., coastal, inland, by a river or a lake, etc.); and
- The level of adaptive capacity of the electricity sector concerned.

To enable the electricity sector to manage this complex issue, what is needed is significant collaboration across stakeholders to strengthen:

- Local climate data and information;
- Solid, but pragmatic, methods for assessing climate change impacts and risks and take advantage of opportunities in the face of uncertainty; and
- Technological, behavioral, and institutional good practice to manage risks and take advantage of opportunities despite uncertainty.

5.3 Favorable Environment for Adaptation Responses Beyond "Business-As-Usual"

Very few climate change adaptation measures are totally new. The majority of today's electricity sector adaptation responses are simply good practice risk management measures undertaken through a lens which considers how the climate is changing.

Most adaptation responses in the electricity sector are primarily motivated by factors other than climate change. In some cases, utilities recognize that these measures have benefits in terms of climate change resilience. This is the case for Eskom's investments in dry cooling technologies for thermoelectric plants, which the company began in the mid-1980s as a response to water scarcity issues. However, in many cases climate risk management measures are adopted as part of "normal" business and it is difficult to single these out as adaptation. For example, actions that improve electricity production, transmission, distribution, and end-use efficiency might also help to manage climate risks, such as reduced output, increased asset downtime, or higher supply disruptions.

With legislation and regulation on adaptation still in its infancy, climate change adaptation is considered optional at best in the electricity sector.[13] To incentivize electricity regulators and utilities in developing countries to go beyond "business-as-usual" and adopt climate change adaptation measures, there needs to be a favorable environment for adaptation, which includes the following elements:

[13] In a few examples, energy regulators have requested more in-depth analysis of climate change impacts as part of environmental assessment obligations. See for example recommendation 39 in Joint Review Panel Environmental Assessment Report—Darlington New Nuclear Power Plant Project. 2011. ISBN: 978-1-100-19116-4.

- Developing standards, regulations, and guidance—There are no obligations, standards, or guidelines in developing countries to manage climate change risks in the electricity sector, nor indeed in most developed countries. This is often a justification for inaction put forward by utilities. Governments, international institutions, and professional bodies (e.g., electricity associations) have roles to play in developing standards, regulations, and guidance which are favorable to adaptation, and can be applied in developing countries. For example, standards and guidance should be applicable in situations when there is a dearth of hydrometeorological data, and they should promote pragmatic approaches to climate risk management.
- Developing sources of finance—The lack of financial support from government and the impossibility of passing costs onto customers explain in many cases the lack of climate change adaptation action in the electricity sector. Developing sources of finance for research and development, or implementation of adaptation measures, by electric utilities in developing countries is a critical condition to improve climate change resilience. This can be done nationally, through the use of differentiated tariffs.[14] For example, the Ontario electricity regulator in Canada has approved a charge on customer bills for government-owned companies servicing remote companies and facing higher fuel costs due to reduced fuel transport on ice roads, and associated increase in air freight as a result of warming.[15]
- Integrating the electricity sector within national adaptation strategies—Finally, developing countries have an opportunity to include actions addressing electricity sector vulnerabilities within their national climate change adaptation strategies.[16] As international climate change adaptation financing for developing countries increases, the electricity sector should work with governments to develop adaptation measures that could be funded.

6 Appendix

Examples of capital expenditures for climate change adaptation investments by utilities (nominal US$)

[14] For further examples of possible funding arrangements see Troccoli, A. 2009. Weather and climate risk management for the energy sector: workshop recommendations. In: Troccoli, A. (ed.) 2009. *Management of Weather and Climate Risk in the Energy Industry. Proceedings of the NATO Advanced Research Workshop on Weather/Climate Risk Management for the Energy Sector Santa Maria di Leuca, Italy, 6-10 October 2008,* Springer.

[15] Peter Fraser, Ontario Energy Board, authors' communication, 22/10/2011.

[16] Presently, few developing countries have included the energy sector within their National Adaptation Plans of Action (NAPAs). A recent analysis found that only 3.7 % of 455 adaptation projects proposed by these NAPAs were related to the energy sector.

Adaptation measures	Climate risks addressed	Cost (million US$)	Timing	Assumptions and references
Budget support to research organization on climate change impacts and adaptation	Overall climate risks and opportunities	12	2002–today	– Financial contribution of CA$1 million and in-kind contribution of 5 full-time equivalent researchers and engineers[a] – Average annual salary of engineers working in universities in Québec: CA$ 66,655 (Institut de la Statistique de Québec 2009) – Average annual salary of technical staff, equivalent to researchers, working in universities in Québec: CA$ 45,653 (Institut de la Statistique de Québec 2009) – Exchange rate of 1 CA$ = 0.97 US$
System wide increase in maximum ice and wind loads, and install special pylons at predefined intervals to avoid cascades of falling pylons	Future increased extreme weather (e.g., wind or ice storms)	875	1999–2007	– Industry sources (Turcotte 2008) – Exchange rate of CA$ 1 = US$ 0.97
Build power grid interconnection with regional partners and invest in de-icing equipment	Future increased extreme weather (e.g., ice storms)	195	2008–2011	
Build new small hydropower plants	Future loss of inflows and hydropower output	125	Planned up to the 2020s	– Capital cost (CAPEX) figures from direct industry sources(Brewster et al. 2009) – Exchange rate of 1 AU$ = 1 US$
Increase storage capacity in existing plants	Future loss of inflows and hydropower output	100	Planned up to the 2020s	
Build new dams	Future loss of inflows and hydropower output	100	Planned up to the 2020s	
Raise height of existing dams	Future loss of inflows and hydropower output	50	Planned up to the 2020s	
Improve turbine runners	Future loss of inflows and hydropower output	17	Planned up to the 2020s	
Undertake major redevelopments on hydropower infrastructure	Future loss of inflows and hydropower output	15	Planned up to the 2020s	
Build new catchment water diversions	Future loss of inflows and hydropower output	11	Planned up to the 2020s	
Upgrade existing water canals	Future loss of inflows and hydropower output	10	Planned up to the 2020s	

(continued)

(continued)

Adaptation measures	Climate risks addressed	Cost (million US$)	Timing	Assumptions and references
Increase dry cooling capacity for thermoelectric generation assets	Reduced cooling water availability	500	1970–2000	– Overall CAPEX for dry cooling is 170 % higher than CAPEX for conventional wet cooling (Lennon 2011) – Average CAPEX to install an entire wet cooling system for a 550 MW coal plant: US$ 37.3 million – Average additional CAPEX to install an entire dry cooling system for a 550 MW coal plant: US$ 26.1 million – Eskom installed 10,500 MW of thermoelectric generation capacity between 1970 and 2000
Install cooling water diversion pipes in one existing power plant	Future increased risk of saline intrusion	0.035	Completed	– Equipment costs could amount to US$ 1.1 million for additional water pipes fitted to the water feed system – Retrofitting costs are estimated to be equivalent to standard industry maintenance costs, namely 3 % of original CAPEX
Raise floor level of buildings housing critical infrastructure in one existing power plant	Future increased flood risk	0.089	Completed	– Two scenarios are considered: one whereby only the floor level where generating motors are located is raised, and one whereby a larger surface area containing motors, pumps and other critical equipment is raised – No structural works are required to raise floor levels – CAPEX is estimated to be US$ 2 and 3.9 million in the two scenarios described above respectively – Retrofitting costs are estimated to be equivalent to standard industry maintenance costs, namely 3 % of original CAPEX
Inspect cooling tower at risk of erosion or landslide	Increased risk of land movement in coastal areas	1.33	N/A	– Average CAPEX for inspecting thermoelectric cooling towers, raising floor levels, and reinforcing the towers' bases as needed is US$ 4.4 million – The power plant concerned has 5 cooling towers – Retrofitting costs are estimated to be equivalent to standard industry maintenance costs, namely 3 % of original CAPEX
Mobile flood defense system	Future increased flood risk	1.25	Completed	– Average CAPEX for a 1-mile long mobile flood defense system is between US$ 1 and 1.5 million[b]

Source authors, based on utilities' interviews

[a] Authors' communication with René Roy, Hydro-Québec (24/10/2011).

[b] Authors' communications with five US vendors (20/12/2011).

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