Accepted Manuscript

Climate Risk Management and the Electricity Sector

Andrea K. Gerlak, Jaron Weston, Ben McMahan, Rachel L. Murray, Megan Mills-Novoa

PII: S2212-0963(17)30157-2
DOI: https://doi.org/10.1016/j.crm.2017.12.003
Reference: CRM 140

To appear in: *Climate Risk Management*

Received Date: 29 September 2017
Revised Date: 9 December 2017
Accepted Date: 14 December 2017

Please cite this article as: A.K. Gerlak, J. Weston, B. McMahan, R.L. Murray, M. Mills-Novoa, Climate Risk Management and the Electricity Sector, *Climate Risk Management* (2017), doi: https://doi.org/10.1016/j.crm.2017.12.003

Climate Risk Management and the Electricity Sector

Andrea K. Gerlak[1,2], Jaron Weston[3], Ben McMahan[4], Rachel L. Murray[5], and Megan Mills-Novoa[2]

Andrea K. Gerlak, PhD (Corresponding author)

University of Arizona

Udall Center for Studies in Public Policy

803 E. First St., Tucson, AZ 85719

agerlak@email.arizona.edu

(520)626-4393 (office)

Abstract: The electric utility industry is an important player in the climate change arena, both as a significant emitter of global emissions and as an industry vulnerable to the impacts of climate change. A climate risk management approach uses risk assessments and decision analyses to identify potential adaptation options. We review the existing literature on climate risk management in the electric utility industry, with a focus on four areas of interest: (1) climate change impacts; (2) measurements of risk; (3) stakeholder engagement and cross-sectoral collaboration; and (4) adaptation actions. Overall, we find significant emphasis on the identification of potential climate change impacts and opportunities for adaptation, but less attention paid to assessments of risk, stakeholder engagement, and cross-sectoral collaboration in climate risk management. We find considerable diversity in the types of adaptation actions, methods for measuring risk, and mechanisms for engaging stakeholders. We offer some suggestions to move beyond more fragmented approaches to climate risk management, including the adoption of more holistic approaches, heightened stakeholder and cross-sectoral engagement, and greater collaboration between researchers and electric utilities.

Highlights

- The electric utility industry is an important player in the climate change arena
- There is diversity in the types of adaptation actions, methods for measuring risk, and mechanisms for engaging stakeholders in climate risk management in the electric utility industry
- There is significant emphasis on the identification of potential climate change impacts and opportunities for adaptation in climate risk management in the electric utility industry

- We find less attention has been paid to assessments of risk, stakeholder engagement, and cross-sectoral collaboration in climate risk management

Keywords: electric utility industry, climate risk, adaptation, stakeholders

Funding: We received funding from the University of Arizona's Office of Research, Discovery & Innovation for this research.

Acknowledgements: We appreciate feedback on an earlier draft from Dan Ferguson and initial thoughts on the review from Ardeth Barnhart.

There are **no competing interests**.

[1] University of Arizona, Udall Center for Studies in Public Policy

[2] University of Arizona, School of Geography and Development

[3] University of Arizona, School of Natural Resources and the Environment, and Eller College of Management

[4] University of Arizona, Institute of the Environment

[5] University of Arizona, Arid Land Studies Program

1. Introduction

The electric utility industry is a key player climate change arena. Globally, the sector emits 35% of total global emissions in 2010 (IPCC, 2014a). The industry also faces considerable vulnerability to climate change impacts due to capital-intensive infrastructure investments associated with resource extraction, power generation, and distribution and transmission, as well as market pressures linked to demographic transitions and a changing climate (U.S. DOE, 2015). The annual cost of electricity production is projected to increase by 14% or $51 billion by 2050 due to warming temperatures (Jaglom et al., 2014). Damage to energy infrastructure can have a considerable impact on social systems, economies, and ecological systems, as illustrated by recent high-profile hurricanes and forest fires in the U.S. (Reed et al., 2010; CHOLETA, 2015). Examples like these indicate the type of natural hazards that are likely to become more frequent, intense, or prolonged as a result of climate change (IPCC, 2014b).

Climate risk management can be seen as a process that incorporates "knowledge and information about climate-related events, trends, forecasts and projections into decision making to increase or maintain benefits and reduce potential harm or losses" (Travis and Bates, 2014, pg. 1). It can serve as an effective framework for assessing adaptation by underscoring the likelihood and implications of potential climate change impacts that adaptation actions are seeking to address (Jones and Preston, 2011). Climate risk management in the form of risk and decision analysis is valuable for expanding the range of potential adaptation options. As a multidisciplinary process necessitating an integrated consideration of socioeconomic and environmental issues process, climate risk management is increasingly preferred over the traditional hazard reduction policies that pursue a narrow roster of options while ignoring the much larger range of theoretically feasible ones (Travis and Bates, 2014). Adopting a 'risk focus' implies that organizations and cross-sectoral collaborations identify specific climate change-related threats and impacts as a starting point for developing adaptation measures. Such adaptation involves action from a broad range of people at different levels in multiple organizations, especially people who have not explicitly considered climate in past decision-making (Willows and Connell, 2003).

We review existing research on climate risk management in the electric utility industry. A focus on the climate risk management in the electric utility industry is critical for three reasons. First, electric utilities are a public good that provide a fundamental societal, cultural, and economic service. Improved climate risk management means utilities are better prepared against climate change related to disruptions of electricity service. Second, electric utilities have a unique financial interdependency with the populations they serve. A major climate change impact could result in rate increases that would add financial stress to customers, in addition to incurred losses to the utility. Finally, the electric utility industry has complex infrastructure exposed to a wide range of threats that, in some geographic regions, are at extreme risk to climate change impacts.

We begin by outlining our methods and approach. Then we highlight our findings around four key areas: (1) climate change impacts; (2) assessment of risk; (3) stakeholder engagement and cross-sectoral collaboration; and (4) adaptation actions. Next, we offer some suggestions to move beyond the fragmented approach to climate risk management we uncover here, including the adoption of more holistic approaches, heightened stakeholder and cross-sectoral engagement, and greater collaboration between researchers and electric utilities.

2. Methods and Approach

To identify relevant papers, we searched in Google, Google Scholar, and the JSTOR, Web of Science, and ScienceDirect databases, using key words such as "climate adaptation" or "climate risk management" and "electric utility sector". We expanded our focus beyond academic publication databases to ensure we captured trade publications, consultancy reports, and government white papers in our search. Papers that did not specifically address both climate risk management in the case of the electric utility sector were rejected outright, while references from each relevant paper were searched for new sources, applying a snowball approach to increase our base of papers. This produced the 33 papers reviewed in this study, including both peer-reviewed articles and grey literature.

The papers reviewed in this study were published between 2002 and 2015, though 75% of papers were published in 2010 or after. Eighteen of the 33 papers were peer-reviewed research articles, 1 was a book chapter, and the remaining 14 are grey literature. The papers ranged in temporal focus from year 2000 to future projections (up to year 2060), although not all papers included future projections. Geographic focus was most often in developed areas of the world, particularly within the U.S. and Europe (two-thirds of papers), but some papers included a global focus or a case study in a less-developed area of the world.

The overall goals of the papers reviewed varied. The grey literature, composed of government agency, consultancy reports, and think tank papers, largely aims to inform the electric utility industry and relevant stakeholders (e.g. regulatory bodies) of strategies and the need for climate risk management. In contrast, peer-reviewed research articles consisted of a mixture of comprehensive articles, some addressed industry wide risks and vulnerabilities from a systems risk perspective (i.e. general conditions that increased vulnerability), while others were more narrowly focused on site or event specific risks (i.e. specific reactions or adaptations to these specific contexts). Overall, the articles included in our analysis ranged from these general assessments of industry wide vulnerability, to specific assessments of aspects or components of that vulnerability, with the responses (additional modeling and analysis, further assessment, suggested adaptations, etc.) generally offered at the scale and level of technical detail in which the risk was initially framed. Table 1 lists the papers reviewed.

Table 1. Papers included in review.

Title	Author	Journal	Year	Publication Type	Location Focus
Vulnerability of Wind Power Resources to Climate Change in the Continental United States	Breslow, P.B., Sailor, D.J.	Renewable Energy	2002	Peer Reviewed Aricle	U.S.
Rebuilding Electrical Infrastructure along the Gulf Coast: A Case Study	Ball, B.	The Bridge	2006	Peer Reviewed Aricle	Mississippi-Louisiana State Line
Electric Utilities: Global Climate Disclosure Framework	CERES, IIGCC, IGCC	CERES	2008	Organizational Research	Global
Physical Impacts of CC on the Western US Electricity System	Coughlin, K., Goldman, C.	Berkeley National Laboratory	2008	Organizational Research	Western U.S.
Adaptation of California's Electricity Sector to Climate Change	Vine, E.	Public Policy Institute of California	2008	Organizational Research	California
Carbon Disclosure Project Electric Utilities	Acclimatise	Acclimatise	2009	Organizational Research	Global
Trends in Water Demand and Water Availability for Power Plants—Scenario Analyses for the German Capital Berlin	Koch, H., Vögele, S., Kaltofen, M. Grünewald, U.	Climate Change	2009	Peer Reviewed Aricle	Germany
Potential Impacts of Climate Change on California's Energy Infrastructure and Identification of Adaptation Measures	Perez, P.	California DoE	2009	Organizational Research	California
Key Technical Challenges for the Electric Power Industry and Climate Change	Beard, L.M., Cardell, J.B., Dobson, I., Galvan, F., Hawkins, D., Jewell,W., Kezunovic, M., Overbye, T.J., Sen, P.K. Tylavsky, D.J.	IEEE Transactions on Energy Conversations	2010	Peer Reviewed Aricle	U.S.
U.S. Energy Industry Response to Recent Hurricane Seasons	Farber-DeAnda, M., Cleaver, M., Lewandowski, C., Young, K.	DOE	2010	Organizational Research	Areas effected by hurrican Katrina
Use of Indicators to Improve Communication on Energy Systems Vulnerability, Resilience and Adaptation to Climate Change	Michaelowa, A., Connor, H., Williamson, L.E. Found In Book: A. Troccoli (ed.), Management of Weather and Climate Risk in the Energy Industry	Springer	2010	Book Chapter	N/A
The Impact of Climate Change on the Electricity Market: A Review	Mideksa, T.K., Kallbekken, S.	Energy Policy	2010	Peer Reviewed Aricle	Global
Climate Change, Nuclear Power the Adaptation Mitigation Dilemma	Kopytko N, Perkins J.	Energy Policy	2011	Peer Reviewed Aricle	Coastal U.S. and Inland France
The Impact of Climate Change on Nuclear Power Supply	Linnerud, K., Mideksa, T.K., Eskeland, G.S.	The Energy Journal	2011	Peer Reviewed Aricle	Europe
Potential Impacts on Hydrology and Hydropower Production under Climate Warming of the Sierra Nevada	Mehta, V.K. Rheinheimer, D.E., Yates, D., Purkey, D.R., Viers, J.H., Young, C.A. Mount, J.F.	Journal of Water and Climate Change	2011	Peer Reviewed Aricle	California

Title	Author	Journal/Source	Year	Publication Type	Location Focus
Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation	Ebinger, J., Vergara, W.	The World Bank	2011	Organizational Research	Global
Adapting to Climate Change Guide for the Energy and Utility Industry	Finley, T., Schuchard, R.	Business for Social Responsibility	2011	Organizational Research	Global
Climate Change, Disasters and Electricity Generation	Urban, F., Mitchell, T.	Strengthening Climate Resilience	2011	Organizational Research	N/A
Business and Climate Change Adaptation Toward Resilient Companies and Communities	Caring for Climate	Caring for Climate	2012	Organizational Research	Global
Energy Efficiency: A Tool for Climate Change Adaptation	Goldman, S., Ungar, L., Capanna, S., Simchak, T.	Alliance to Save Energy	2012	Organizational Research	U.S.
Estimating Impacts of Warming Temperatures on California's Electricity System	Sathaye, J.A., Dale, L.L., Larsen, P.H., Fitts, G.A., Lewis, K.K., de Lucena, S.M., Pereira, A.F.P.	Global Environmental Change	2012	Peer Reviewed Aricle	California
Energy Sector Vulnerability to Climate Change: A Review	Schaeffer, R., Szkloré, A.S., de Lucena, A.F.P., Borba, B.S.M.C., Nogueira, L.P.P., Fleming, F.P., Troccoli, A., Harrison, M., Boulahya, M.S.	Energy	2012	Peer Reviewed Aricle	N/A
Vulnerability of US and European Electricity Supply to Climate Change	van Vliet, M.T., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P. Kabat, P.	Nature Climate Change	2012	Peer Reviewed Aricle	U.S. and Europe
Climate Change and Energy Supply and Use	Wilbanks, T., Bilello, D., Schmalzer, D. Scott, M.	DoE	2012	Peer Reviewed Aricle	U.S.
Susceptibility to the European Electricity Sector to Climate Change	Klein, D.R., Olonscheck, M., Walther, C. Kropp, J.P.	Energy	2013	Peer Reviewed Aricle	Europe
New York City Utility Resilience	NYC	City of New York	2013	Organizational Research	New York City
Impacts of, and Adaptation Options to, Extreme Weather Events and Climate Change Concerning Thermal Power Plants	Sieber, J.	Climate Change	2013	Peer Reviewed Aricle	N/A
U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather.	Zamuda, C., Mignone, B., Bilello, D., Hallett, K.C., Lee, C., Macknick, J., Newmark, R., Steinberd, D.	DoE	2013	Organizational Research	U.S.
Climate Risk Management Approaches in the Electricity Sector	Audinet, P., Amado, J.C., Rabb, B.	Weather Matters for Energy	2014	Peer Reviewed Aricle	Global
Improving the Usability of Integrated Assessment for Adaptation Practice: Insights from the U.S. Southeast Energy Sector. Environmental Science & Policy	de Bremond, A., Preston, B.L. Rice, J.	Environmental Science & Policy	2014	Peer Reviewed Aricle	Southeast U.S.
Envisioning Resilient Electrical Infrastructure: A Policy Framework for Incorporating Future Climate Change into Electricity Sector Planning	Nierop, S.C.A.	Environmental Science & Policy	2014	Peer Reviewed Aricle	Developed Countries
Impacts of CC on Electric Power Supply in the Western US	Bartos, M.D., Chester, M.V.	Nature Climate Change	2015	Peer Reviewed Aricle	Western U.S.
Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions	DOE	DoE	2015	Organizational Research	U.S.

3. Climate Change and Electric Utilities: Impacts, Risks, Stakeholders, & Adaptation

In this section, we summarize some of the key themes that span across the literature regarding how the electric utility industry has been assessed in terms of climate change impacts, the assessment of risk, stakeholder engagement and cross-sectoral collaboration, and adaptation actions. We develop these themes by drawing on broader issues raised in decision support and climate information research (e.g. Kettle et al., 2014; Andersson-Skold et al., 2015; Dourte et al., 2015; Lunt et al., 2016) along with a more bottom-up method of interpretive synthesis that draws themes from a reading and interpretation of the papers in the review (Weed, 2008). The Appendix reports detailed findings around the research themes presented below. Image 1 below displays the presence of these themes in the papers reviewed.

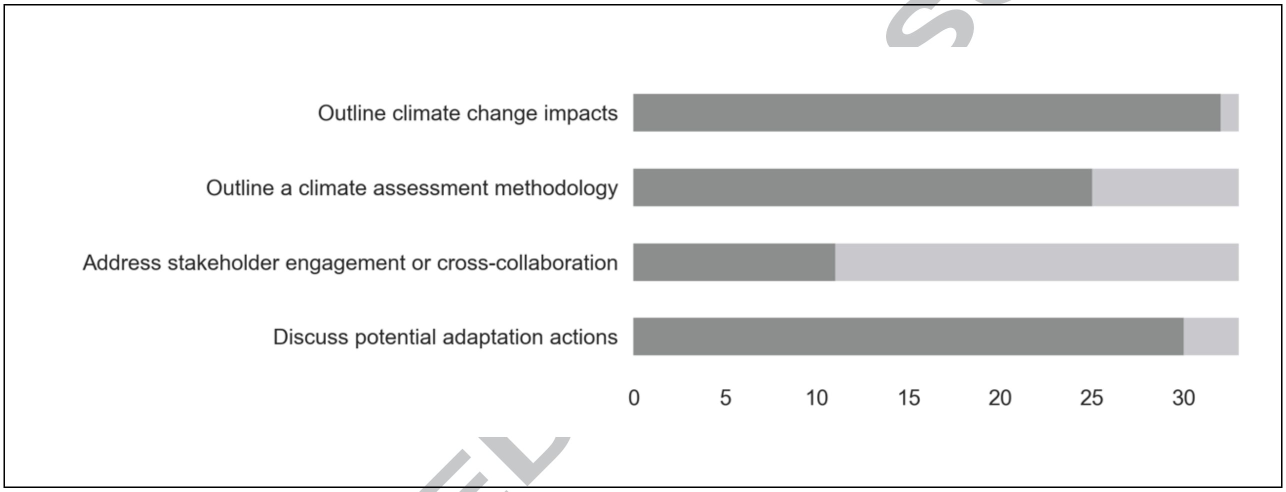

Image 1. Presence of themes in papers reviewed.

3.1.Climate change impacts

Increasing temperatures are a fundamental component of climate risk assessments for the energy industry. These increases will alter seasonal demand for energy, increase the vulnerability of power generation and transmission infrastructure deployed at marginal operating temperatures, increase fire risk as elevated temperatures decrease soil and vegetation moisture, and affect water resources via long term drought (increased aridity) and declining snowpack (warming winters) (Coughlin and Goldman, 2008; Ebinger, 2011; Wilbanks et al., 2012). Increasing temperatures also reduce energy demand in cooler climates, resulting in decreased energy costs for households, but decreased revenue for utilities. Extreme temperatures can have severe consequences if they cause spikes in demand that cause brownouts or blackouts, or if extended power outages unrelated to climate and environmental conditions (e.g., human error, system failure, etc.) occur during periods of extreme heat. Increasing energy costs associated with extended warm seasons (and shorter cold seasons) can have negative impacts on economically marginalized populations who may lack the ability to pay for heating or cooling resources during winter and summer months (Hernández and Bird, 2010; Miller, 2014; Spector, 2016).

The papers in our review discussed climate and environmental impacts that were of particular concern to electric utilities. A majority of the papers, or 32 out of 33 focused on the potential impacts of climate change on the energy industry. Some of the authors took a general approach to discuss challenges associated with climate change at a systems level (e.g. Ebinger, 2011; Klein et. al., 2013; Audinet et al., 2014; Bartos and Chester, 2015) while others provided specific examples of how these changes might affect (or have affected) the energy industry (e.g. Ball, 2006; Mehta et al., 2011; Jayant, 2012). In terms of specific impacts and risks associated with climate change, the two primary factors most often discussed were temperature and water supply.

Most of the research, or 30 our 33 papers, addressed extreme weather events and environmental extremes, including heat waves and temperature extremes, high intensity precipitation events, inland flooding, hurricanes, tropical storms and coastal flooding, ice storms, and high intensity wind events. A U.S. DOE report on the vulnerabilities of electric utilities to climate change and extreme weather provides the most comprehensive overview of many of these topics (Zamuda et al., 2013), but a number of these assessments focused on geographically specific impacts (e.g. hurricanes, ice storms, extreme precipitation and flooding, etc.). Within the discussion of extreme climatic events, some authors noted the compounding effect of climate change on extreme weather extremes (Schaeffer et al., 2012). Climate change is projected to increase the intensity and frequency of some extreme events such as tropical storms and flooding, with potential consequences for the energy sector (Coughlin and Goldman, 2008; Knutson et al., 2010; Zamuda et al., 2013).

A majority, or some 23 out of 33 papers, in our review focused on specific threats, such as the impact of a changing climate on electric infrastructure (e.g., Coughlin and Goldman, 2008; Perez, 2009) – whereas another 20 papers focused on a general level of concern that arose based on mid- to long-term climate projections, and the uncertainty and disruption that these projections might suggest (e.g., Wilbanks et al., 2012; Zamuda, 2013). A few researchers used scenario-based projects to focus on the specific consequences of hypothetical scenarios (e.g., Koch et al., 2009; Sathaye et al., 2011), although the usefulness of these scenarios is limited by the specificity of any predictions, and how plausible or useful these predictions might in helping to plan for future climate conditions. In general, uncertainty in climate models and the relatively coarse measures of future climate conditions, made specific operational planning for utilities difficult to implement given the lack of data tailored to conditions of interest for the utilities.

Few papers included social factors such as demographic growth, land use change, or policy and regulatory frameworks that interact with climate, weather, and environment (with the exceptions of Coughlin and Goldman, 2008; Skaggs et al., 2012). Discussions of these social factors were generally limited to specific implications that climate and environmental factors might have on energy industry operations, management, and planning.

3.2.Assessing climate risk

There are implications for electric utilities associated with long-term climate change and extreme weather events. A risk management framework would facilitate a process by which utilities could assess climate related risks and develop plans based on projected impacts. Industry representatives and analysts anticipate that extreme events and climate change pose varying degrees of risk to electric utilities, but the papers that discuss process or methods do not present any observably uniform methods for assessing risks, and one-third of the papers in our review did not address any specific risk assessment methodologies or metrics that identified specific climate impacts.

Papers in our review generally focused on systemic vulnerability within the components of the utility system – that is on the overarching impacts that might be observed at generating stations, and across transmission and distribution infrastructure, given present and future climate conditions. This systemic perspective focused attention on potential instability and disruption introduced via specific events (e.g. blackouts, demand spikes, transmission interruption), as well as material risks associated with ongoing operations and maintenance costs (wear, loss, etc.). This distinction is due to the pragmatic constraints of these analyses: papers that were general assessments of the industry were oriented toward abstract and systemic risk that could threaten business stability or have long term implications (Wilbanks et al., 2012; Nierop, 2014), while targeted examples were more likely to provide specific discussions of operational risk that could affect long term profitability and sustainability (Lucena et al., 2010; Mehta et al., 2011), but linked to specific and identifiable impacts within that particular context.

Different approaches to characterizing risk reflect a persistent desire to predict vulnerabilities faced by, and opportunities available to, electrical utilities. But as De Bremond et. al. (2014) point out, these “third generation” characterizations of risk, focus on assessing vulnerability and do little to address fourth and fifth generation assessments that include evaluation of the effectiveness of different adaptation options and whether they are successful at reducing risk. This suggests that a comprehensive approach to assessing risk and vulnerability must include more than a simple assessment of risks and vulnerabilities. Comprehensive approaches must also evaluate the role of social and institutional factors that shape these risks (e.g. market drivers, policy environments, regulatory frameworks, social and human consequences, etc.), and engage in ongoing evaluation to assess how adaptation plans are being developed and implemented, and whether they are successful in reducing risk and vulnerability.

3.3.Stakeholder engagement and cross-sectoral collaboration

Although the majority of papers in our review highlighted the need for or importance of stakeholder engagement or cross-sector collaboration in climate risk management, just over one-third of the papers in our review, or 11 of 33 papers, actually discuss stakeholder engagement or cross-sectoral collaboration. In climate risk management, stakeholders can be broadly seen as "investors, lenders, insurers, market and financial analysts, governments and regulatory agencies, consumers, local communities and NGOs" (Acclimatise, 2009, pg. 4). In some cases, stakeholder engagement means promoting greater interaction between private firms such as energy companies and public institutions such as state regulators to enable more effective adaptive responses (e.g. de Bremond et al., 2014). Others emphasize that adaptation should be led by utilities, but that there must be "intensive cooperation between utilities, utility regulators, local and supralocal goverments" since utilities lack the authority to implement all necessary adaptive actions (e.g, Nierop, 2014, pg. 18). Consumers and investors are also highlighted as key stakeholders in prompting utilities to expand renewable energy supply portfolios (Finley and Schuchard, 2011), and collaborators with utilities in the generation of renewable energy (Acclimatise, 2009).

Some narrowly define stakeholder engagement. For example, in their study of early adopters of climate risk management in the electricity sector, Audinet et al. (2014) frame stakeholder engagement more as industry disclosure of their actions to investors and stakeholders. In contrast, the U.S. Department of Energy (DOE) (2015) asserts the central role play by the DOE in convening stakeholders and highlights examples of stakeholder engagement in the U.S. This includes the Bonneville Power Administration working with stakeholders to reach agreements on proactive vegetation maintenance to prevent power outages caused by vegetation interfering with powerlines; PG&E engaging with state and local stakeholders to develop strategies to adapt to reductions in snowpack in the Sierra Nevada Mountains so as to maintain hydropower generation; and natural resource conservation stakeholder and industry collaboration around coastal power generation facilities planning.

Some studies are also calling attention to the need for cross-sectoral collaboration. Schaeffer et al. (2012) highlight two main cross-sector impacts on energy from climate change: competition for water resources (in electricity generation, oil refining and irrigation of energy crops) and land competition (for biofuels production). The U.S. DOE (2013) similarly highlights interdependencies between the energy sector and other sectors, such as water and land systems. Water pumping, transport, and treatment require energy. Similarly, energy production requires water for extraction, cooling, and processing. The transportation sector requires energy for motive power, while the energy sector needs transportation to provide the necessary resources, like coal, oil, and natural gas, to operate. In addition, the communications sector requires electricity to operate; the energy sector relies on communication systems to monitor and manage the electric grid. Although we see growing attention to the need for cross- sectoral collaboration, we do not uncover examples of it in practice.

3.4.Adaptation actions

The majority – or 30 of 33 papers -- in our review discuss adaptation to climate change in the electric utility industry. Although they do not discuss adaptation in any detail, almost all of the papers reviewed here cite adaptation as necessary. In terms of infrastructural and behavioral adaptation actions, we found the most common adaptation actions were investing in cooling and water efficiency technologies for power plants, particularly when siting new infrastructure, or hardening infrastructure (through retrofitting or reinforcing infrastructure), along with improved internal planning for climate change. We found a wide variety of proposed adaptation options, including diversifying energy portfolios and better demand side management. As an example, several papers offered in-depth descriptions of the best types of infrastructure hardening, with pros and cons and a targeted geographic area (DoE, 2010; NYC, 2013; Nierop, 2014).

Our analysis of the adaptation actions revealed critical differences in recommendations, based on the topic and geographic focus of the paper. Papers focusing on power plants and power generation, for example, were much more likely to suggest efficiency improvements for power plants (Koch et al., 2009; Mehta, 2011; Kopytko, 2011). Papers that considered the entire electricity sector typically gave a more complete set of recommendations for utilities, such as infrastructure hardening and improved demand side management (Vine, 2008; DoE, 2015). Research on adaptation actions in the U.S., for example, was focused more narrowly on improving technologies and improving information and decision-making practices (e.g. Wilbanks et al., 2012; Zamuda et al., 2015; van Vilet et al., 2012), with less emphasis on stakeholder engagement, and enabling new policies (Zamuda et al., 2013).

It was rare for papers to be based on direct communication with utilities focused on specific events to analyze opportunities for climate adaptation, but the papers that did so provided a notably different perspective. These papers identified adaptation in the electric utility sector as an incremental process (Finley and Schuchard, 2011; de Bremond, 2014), tied to the long-term decision making required to design and implement large scale utility infrastructure projects. Because electric utility infrastructure is capital-intensive, damage to infrastructure is a key concern. However, since existing infrastructure required considerable capital investments, electric utilities find full-scale infrastructure upgrades economically infeasible (Audient et al., 2014). Instead, electric utilities have made smaller infrastructure upgrades incrementally, an approach that is predicted to continue (de Bremond, 2014; Audient et al., 2014; Finley and Schuchard, 2011). A key theme among these papers was the call for leadership from within the electric utility on this issue (e.g, Ball, 2006). Without a focus on adaptation that originates from within the company, adaptation is seen as nearly impossible. With internal attention and leadership, however, an electric utility with cooperation from state regulatory agencies, can develop adaptation actions that strategically dovetail with other plans (Nierop, 2014).

4. Synthesis and Future Directions

Overall, we found that the majority of papers reviewed here focused both on identifying potential climate change impacts and providing suggestions for adaptation. Measuring the risk of climate change impacts and engaging stakeholders were also themes, but not as strongly covered in the papers reviewed. We found diversity in the types of adaptation actions, methods for measuring risk, and mechanisms for engaging stakeholders across the papers, revealing the larger context of how climate change is experienced and adapted to by the electric utility industry around the world.

The more fragmented approach to climate risk management that we uncover here with regard to electric utilities falls short of the ideal of the risk and decision analysis needed to support adaptation to climate change. To move beyond this more fragmented approach, we outline some potential next steps to help advance more holistic risk management, heightened stakeholder engagement and cross-sector collaboration and partnerships between researchers and utilities in climate risk management.

4.1. Emphasizing holistic approaches to adaptation to climate vulnerability

Overall, we found that extreme weather events and flooding were the most commonly emphasized hazards in the climate risk management literature. Extreme weather events and flooding may represent the most substantial threats to the electric utility industry, but they do not account for all impacts, especially for utilities outside of regions where those threats exist. As such, research should be invested into areas where gaps in research on climate change impacts to electric utilities exist (e.g. wildfire or changes to wind patterns) to provide a more complete understanding of risks and potential adaptation strategies. The recent catastrophic fires in northern California speak to this and suggest potential liability for utilities that fail to provide data to indicate where power lines present risk for wildfires (Gafni, 2017).

In particular, a focus that expands the risk assessment to include interactions within the system is an important aspect that would expand the usefulness of climate risk management for utilities, and would give researchers targets for future research on systems level vulnerability. One example from our own research would be the relationship between drought – and specifically water availability and competition over scarce water resources in the Southwest – and the changing dynamics of temperature, snowpack, streamflow timing, and energy portfolio management (i.e. coal powered vs. natural gas vs. renewables) (Gerlak and McMahan, 2017).

Decision making and planning for these eventualities are taking place within the context of changing regulatory frameworks (i.e. uncertainty about the U.S. EPA Clean Power Plan), and changing market conditions that may provide an independent driver that further pushes utilities away from coal powered generating capacity, and towards natural gas and renewables. This reveals that complex challenges utilities face are not necessarily tied to specific events or short-term conditions, although they are frequently exacerbated by these events. Rather, many of the most difficult challenges, involve the gradual accumulation of interrelated systemic vulnerabilities that span across different areas of expertise and management, and across both political and private-sector decision making frameworks.

Sustainable solutions to these challenges require a similarly complex level of engagement within and across these interrelated factors (Preston et. al., 2016). We find that little of the existing research addresses the intersection of overlapping impacts in terms of the amplified effect they have on specific events, or how a changing climate affects how future climate impacts are understood. Integrating a perspective on future baseline climate conditions is a particularly important aspect since it will shape regional demand patterns, energy supply, and threats to infrastructure going forward.

A holistic risk management perspective embeds climate risk within a larger suite of risks a company or sector may face (Cardona, 2004), but this approach may minimize the role of climate compared to other more established or well-defined risks. This could leave a company or industry vulnerable if and when these dynamics change, or when additional data and information comes to light. Conversely, targeted risk assessments focused on specific and sometimes de-contextualized assessments of risk may provide additional detail about a given exposure or hazard, but can miss vulnerabilities associated with their connection to social or economic systems. The assumption of a rational and uniform response to a given risk that is embedded in some forms of risk management thinking may also ignore other dynamics that drive risk management and adaptation planning such as the perceptions associated with these risks, the values that may drive actions and responses, and the obstacles or barriers to action that are not well characterized by a detached analysis of risks and vulnerabilities (Slovic et al., 2004).

4.2. Ample talk, little action on stakeholder engagement, cross-sector collaboration, and adaptation action

Although we find recognition of the importance of stakeholder engagement and cross-sector collaboration in climate risk approaches in the electricity sector, we find little demonstrable action. Among other things, stakeholder engagement and collaboration can serve to strengthen local climate data and information, further develop methods for assessing risk, and promote a broad suite of technological, behavioral, and institutional practices necessary for greater resilience (Audinet et al., 2014, pg. 58). Given the interconnected, networked nature of energy systems, stakeholder coordination and engagement is needed for successful implementation of any adaptation strategy (US DoE, 2015, pg. 11-3), and will depend on the contributions of stakeholders and researchers who engage in increasingly collaborative relationships, that grow and develop over time (Meadow et. al., 2015). This concept is increasingly recognized, as outlined in the U.S. National Climate Assessment (Skaggs et al., 2012), but we find it not well executed in the papers in this review.

There is a growing recognition of the interdependencies of utilities with other sectors, including water, transport, and information and communications technology, among others (Metz et al., 2016). Yet, it remains a difficult task to assess the complex inter-relationships and cascading effects associated with climate change impacts and risks associated with climate change (Lucena et al., 2010; Schaeffer et al., 2012; DoE, 2014; Garfin et al. 2016). Nonetheless, because failure in one sector can lead to a cascade of failures (URS, 2010), greater cross-sectoral collaboration is needed in climate risk management. Ball et al. (2016) highlights the necessity of cross-sectoral responses to the impact of Hurricane Katrina on the electricity infrastructure of the Louisiana Coast. Numerous Louisiana utilities collaborated amongst one another and worked to address the destructive impacts of the hurricane on infrastructure and customers. This experience now informs efforts for building internal disaster response capacity and continued collaboration across sectors involved in planning for extreme weather events.

4.3. Partnerships between researchers and utilities

As research on the topic of climate risk management grows, it is important that researchers delineate more coherent foci to their research to create more relevant and practical climate risk management solutions. We were struck by an overall lack of practical application and this may perhaps be the most noteworthy area for improvement in this body of research. The dominant approach (in approximately two-thirds of the papers reviewed here) was a more top-down approach analyzing climate risk management from a perspective external to the electric utility. In contrast, a more "bottom-up" approach included the electric utility perspective as central, whether by interviewing utilities, using case scenarios, or including utility employees as authors. Interestingly, we note that the major suggestions from the approaches – increased demand side management, increased efficiency improvements, and improved cooling towers – were rarely implemented by any of the utilities in the case studies.

To mitigate this growing disconnect between researchers and practitioners, we argue for more bottom-up approaches where researchers collaborate with electric utilities in designing research and conducting climate risk management. This supports a needed shift from science-driven assessments to policy-driven assessments (Fussel, 2007) and adoption of an iterative process of collaborative assessment where quantitative models and qualitative stakeholder products are linked as tools to combine scientific and stakeholder knowledge and insight (Harrison, 2013). Identifying the scope and extent of climate change impacts and crafting solutions to these impacts is an important process that is dependent on collaboration between the electric utility industry, governments, and researchers (e.g. Schaeffer et al., 2012).

In addition, where climate related risk was considered as one of many components of a larger process of risk management (e.g. Beasley et al., 2005), isolating climate-specific risks was not seen as an efficient way of managing a risk portfolio. In the absence of specific cost/benefit information about climate impacts, a comprehensive (or 'enterprise') risk management perspective may limit response or action, given lack of specific points of intervention. This is especially the case if the projected costs of climate change are unknown, or seen as smaller or less threatening than other enterprise risk management concerns. Given the potential future climate impacts, these costs may be much higher, and some researchers suggest that anticipatory planning that integrates climate risk management may be more efficient and cost effective than plans developed in reaction to future crises (Quay, 2012). By exploring which is the most efficient strategy, it may reveal that integrating climate risks into the utility risk management portfolio could reduce overall costs and help to build more sustainable policies and practices going forward. Bottom-up participatory approaches may lead to better understandings of specific climate risks. This in turn can demonstrate the utility and the cost-effectiveness of mitigating specific climate risks, and the importance of inclusion of climate and environmental risks within the larger package of enterprise risk management priorities, especially as the potential impact of climate is better understood.

References

Acclimatise, 2009. Building Business Resilience to Inevitable Climate Change. Carbon Disclosure Project Report. Global Electric Utilities. Oxford.
Andersson-Sköld, Y., 2015. An integrated method for assessing climate-related risks and adaptation alternatives in urban areas. Climate Risk Management. 7, 31-50.
Audinet, P., Amado, J.C., Rabb, B., 2014. Climate risk management approaches in the electricity sector. Weather Matters for Energy. 17(1), 17-64.
Ball, B., 2006. Rebuilding electrical infrastructure along the gulf coast: a case study. The Bridge. 36(1), 21-26.
Bartos, M.D., Chester, M.V., 2015. Impacts of climate change on electric power supply in the western US. Nat. Clim. Change. 5(8), 748-752.
Beard, L.M., Cardell, J.B., Dobson, I., Galvan, F., Hawkins, D., Jewell, W., Kezunovic, M., Overbye, T.J., Sen, P.K. Tylavsky, D.J., 2010. Key technical challenges for the electric power industry and climate change. IEEE Transact. on Energy Conversations. 25(2), 465-473.
Beasley, Mark S., Richard Clune, and Dana R. Hermanson. 2005. Enterprise risk management: An empirical analysis of factors associated with the extent of implementation. Journal of accounting and public policy. 24.6, 521-531.
Breslow, P.B., Sailor, D.J., 2002. Vulnerability of wind power resources to climate change in the continental United States. Renewable Energy. 27(4), 585-598.
Cardona, O.D. 2004. The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management. Mapping vulnerability: Disasters, development and people. 17, 37-51.
Ceres, Institutional Investors Group on Climate Change, Investor Group on Climate Change, 2008. Electric utilities: global climate disclosure framework.
CHOLETA. 2015. Mitigating the wildfire risk to electric utilities. Edmond, OK: CHOLETA.
Coughlin, K., Goldman, C., 2008. Physical impacts of climate change on the western US electricity system: a scoping study. Berkeley National Laboratory, Berkeley.
De Bremond, A., Preston, B.L. Rice, J., 2014. Improving the usability of integrated assessment for adaptation practice: insights from the U.S. southeast energy sector. Environ. Sci. & Pol. 42, 45-55.
Dourte, D.R., Fraisse, C.W., Bartels, W.L., 2015. Exploring changes in rainfall intensity and seasonal variability in the Southeastern U.S.: Stakeholder engagement, observations, and adaptation. Climate Risk Management. 7, 11–19.
Ebinger, J., 2011. Climate impacts on energy systems: key issues for energy sector adaptation. Washington, DC: World Bank.
Farber-DeAnda, M., Cleaver, M., Lewandowski, C., Young, K., 2010. Hardening and resiliency: US energy industry response to recent hurricane seasons. U.S. Department of Energy, Washington, DC: U.S. Department of Energy.
Finley, T., Schuchard, R., 2011. Adapting to climate change guide for the energy and utility industry. Business School of Responsibility, San Francisco.
Fussel H.M., 2007. Adaptation planning for climate change: concepts, assessment approaches, and key lessons. Sustainable Science. 2, 265-275.
Gafni, Matthias. 2017. PG&E helped stall effort to map risky power lines prone to wildfires. *The Mercury News*, October 21, 2017 (accessed November 30, 2017). At http://www.mercurynews.com/2017/10/21/pge-helped-stall-effort-to-map-risky-power-

lines-prone-to-wildfires/?utm_source=Water+Deeply&utm_campaign=1ba1e4e69f-EMAIL_CAMPAIGN_2017_10_26&utm_medium=email&utm_term=0_2947becb78-1ba1e4e69f-117789629&mc_cid=1ba1e4e69f&mc_eid=7aebe5335e

Garfin, G., LeRoy, S., McMahan, B., Black, M., Roh, B., 2016. Preparing for High Consequence, Low Probability Events: Heat, Water & Energy in the Southwest. Report to the U.S. Bureau of Reclamation, from the project Enhancing Water Supply Reliability. Tucson, AZ: Institute of the Environment.

Gerlak, A.K. and McMahan. 2017. Climate Risk Assessment and Impacts to Tucson Electric Power. Final Report. Tucson, AZ: University of Arizona.

Goldman, S., Ungar, L., Capanna, S. Simchak, T., 2012. Energy efficiency: a tool for climate change adaptation. Washington, DC: Alliance to Save Energy,

Harrison, P.A., 2013. Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptations, and vulnerability in Europe. Reg. of Environ. Change. 13, 761-780.

Hernández, D. and Bird, S. 2010. Energy Burden and the Need for Integrated Low-Income Housing and Energy Policy. Poverty & Public Policy. 2, 5–25.

IPCC, 2014a, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.

IPCC, 2014b, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY: Cambridge University Press.

Jaglom, W.S., 2014. Assessment of projected temperature impacts from climate change on the U.S. electric power sector using the Integrated Planning Model. Energy Policy. 73, 524-539.

Jayant, A., Sathaye, L.L., Dale, P.H., Larsen, G.A., Fitts, K.K., Lewis, S.M. de Lucena, A.F.P., 2012. Estimating impacts of warming temperatures on California's electricity system. Global Environ. Change. 23(2), 499-511.

Johnson, J.M., 2014. Quantifying the economic risk of wildfires and power lines in San Diego County. Master's thesis, Duke University.

Jones, R.N., Preston, B.L., 2011. Adaptation and risk management. WIREs Clim. Change. 2, 296–308.

Kettle, N.P., 2014. Integrating scientific and local knowledge to inform risk-based management approaches for climate adaptation. Climate Risk Management. 4-5, 17-31.

Klein, D.R., Olonscheck, M., Walther, C. Kropp, J.P., 2013. Susceptibility to the European electricity sector to climate change. Energy. 59, 183-193.

Knutson, T. R., McBride, J.L, Chan, J., Emanuel, K., Holland, G., Landsea, I., Kossin, J.P., Srivastava, A.K., and Sugi, M. (2010) Tropical cyclones and climate change. Nature Geoscience. 3, 157-163.

Koch, H., Vögele, S., Kaltofen, M. Grünewald, U., 2009. Trends in water demand and water availability for power plants—scenario analyses for the German capital Berlin. Climate Change. 110(3), 879-899.

Kopytko N, Perkins J., 2011. Climate change, nuclear power the adaptation mitigation dilemma. Energy Pol. 39(1), 318-333.

Kristin L., Mideksa, T.K., Eskeland, G.S., 2011. The impact of climate change on nuclear power supply. The Energy Journal. 32(1), 149-168.

Lucena A.F.P., Szklo A.S., Schaeffer R., 2010. Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. Global Environ. Change. 20(2), 342-350.
Lunt, T., Jones, A.W., Mulhern, W.S., Lezaks, D.M.P., Jahn, M.M., 2016. Vulnerabilities to agricultural production shocks: An extreme, plausible scenario for assessment of risk for the insurance sector. Climate Risk Management. 13, 1–9.
Meadow, A.M., Ferguson, D.B., Guido, Z., Horangic, A., Owen, G., 2015. Moving toward the deliberate co-production of climate science knowledge. Weather, Climate, and Society. 7, 179-191.
Mehta, V.K. David E. R., Yates, D., Purkey, D.R., Viers, J.H., Young, C.A. Mount, J.F., 2011. Potential impacts on hydrology and hydropower production under climate warming of the Sierra Nevada. Journal of Water and Clim. Change. 2(1), 29-43.
Meinke, H., R. Nelson, P. Kokic, R. Stone, R. Selvaraju, and W. Baethgen. "Actionable climate knowledge: from analysis to synthesis." Climate Research 33 (2006): 101-10.
Metz, A., Darch, D.G., Workman, M, 2016. Realising a climate-resilient UK electricity and gas system. Proceedings of the Institution of Civil Engineers. 169(1), 30-43.
Michaelowa, A., Connor, H., Williamson, L.E., 2010. Use of indicators to improve communication on energy systems vulnerability, resilience and adaptation to climate change. In Management of Weather and Climate Risk in the Energy Industry, edited by Alberto Troccoli. Netherlands: Springer, 69-87.
Mideksa, T.K., Kallbekken, S., 2010. The impact of climate change on the electricity market: a review. Energy Policy. 38(7), 3579-3585.
Miller, J., 2014. Heat or Eat? New York Tackles Energy Costs and Climate Change, The Island Press Urban Resilience Project, Washington, D.C.
Nierop, S.C.A., 2014. Envisioning resilient electrical infrastructure: a policy framework for incorporating future climate change into electricity sector planning. Environ. Sci. & Pol. 40, 78-84.
City of New York., 2013. A stronger, more resilient New York. NY: City of New York.
Park, J., Hopkins, N., 2012. Business and climate change adaptation toward resilient companies and communities. NY: Caring for Climate.
President's Council of Advisors on Science and Technology (PCAST), 2015. Actions to Catalyze and Support Private-Sector Adaptation Efforts. Washington, DC: White House.
Perez, P., 2009. Potential impacts of climate change on California's energy infrastructure and identification of adaptation measures. Sacramento, CA: California Energy Commission.
Preston, B., 2010. Invasive plant species increase wildfire risk. SF Gate, April 11, 2010. Accessed June 23, 2017. http://www.sfgate.com/green/article/Invasive-plant-species-increase-wildfire-risk-3192514.php
Preston, B.L., 2016. Resilience of the U.S. electricity system: a multi-hazard perspective. Department of Energy. Washington D.C.
Quay, R. 2010. Anticipatory governance: A tool for climate change adaptation. Journal of the American Planning Association. 76(4), 496-511.
Reed, D.A., Powell, M.D., Westerman, J.M., 2010. Energy infrastructure damage analysis for Hurricane Rita. Natural Hazards Review. 11(3), 102–9.
Sathaye, J., Dale, L., Larsen, P., Fitts, G., Koy, K., Lewis, S., Lucena, A., 2011. Estimating risk to California energy infrastructure from projected climate change. Berkeley, CA: Berkeley National Laboratory.

Schaeffer, R., Szkloré, A.S., de Lucena, A.F.P., Borba, B.S.M.C., Nogueira, L.P.P., Fleming, F.P., Troccoli, A., Harrison, M., Boulahya, M.S., 2012. Energy sector vulnerability to climate change: a review. Energy. 38(1), 1-12.

Sieber, J., 2013. Impacts of, and adaptation options to, extreme weather events and climate change concerning thermal power plants. Climate Change. 121(1), 55-66.

Simms-Gallagher, K. ed. 2009. Acting in Time on Energy Policy. Washington, DC: Brookings Institute Press.

Skaggs, R., Janetos, T.C., Hibbard, K.A., Rice, J.S., 2012. Climate and energy-water-land system interactions. Pacific Northwest National Laboratory.

Slovic, P. et al., 2016. Risk as analysis and risk as feelings: Some thoughts about affect, reason, risk, and rationality. Risk Analysis. 24(2), 311-322.

Spector, J. 2016. Why Poor Americans Have Some of the Highest Electricity Bills. *The Atlantic*, April 18, 2016.

Travis, W.R., Bates, B., 2014. What is climate risk management? Climate Risk Management. 1, 1-4.

Urban, F., Mitchell, T., 2011. Climate change, disasters and electricity generation. Strengthening Clim. Brighton, UK: IDS. Strengthening Climate Resilience Discussion Paper 8.

U.S. Department of Energy (USDOE), 2015. Climate Change and the U.S. Energy Sector: Regional vulnerabilities and resilience solutions. Washington, DC: DOE.

United Research Services Corporation (URS), 2010. Adapting Energy, Transport & Water Infrastructure to the Long-term Impacts of Climate Change. London, UK: URS.

Van Vliet, M.T., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P. Kabat, P., 2012. Vulnerability of US and European electricity supply to climate change. Nat. Clim. Change. 2(9), 676-681.

Vine, E., 2008. Adaptation of California's electricity sector to climate change. San Francisco, CA: Public Policy Institute of California.

Weed, M., 2008. A Potential Method for the Interpretive Synthesis of Qualitative Research: Issues in the Development of 'Meta-Interpretation'. International Journal of Social Research Methodology. 11(1), 13-28.

Westerling, Anthony L., et al. 2006. Warming and earlier spring increase western US forest wildfire activity. Science. 313(5789), 940-943.

Wilbanks, T.B., Schmalzer, D., Scott, M., Arent, D., Buizer, J., Chum, H., Dell, J., Edmonds, J., Frando, G., Jones, R., Rose, S., Roy, N., Sanstad, A., Seidel, S., Weyant, J., Wuebbles, D., 2012. Climate change and energy supply and use. Washington, DC: Oak Ridge National Laboratory and U.S. Department of Energy.

Willows, R., Connell, R., 2003. Climate adaptation: risk, uncertainty and decision-making. UKCIP Technical Report. Oxford, UK.: United Kingdom Climate Impacts Programme.

Zamuda, C., Antes, M., Gillespie, C.W., Mosby, A., Zotter, B., 2015. Climate change and the U.S. energy sector: regional vulnerabilities and resilience solutions. Washington, DC: U.S. Department of Energy

Zamuda, C., Mignone, B., Bilello, D., Hallett, K.C., Lee, C., Macknick, J., Newmark, R., Steinberg, D., 2013. U.S. Energy sector vulnerabilities to climate change and extreme weather. Washington, DC: U.S. Department of Energy.

Appendix.

Research themes	# (%) of papers	Papers (author last name and year)
Outline climate change impacts	32 (97%) papers	Breslow and Sailor 2002; Ball 2006; Coughlin and Goldman 2008; CERES et al. 2008; Vine 2008; Koch et al. 2009; Acclimatise 2009; Perez 2009; Beard et al. 2010; Mideksa and Kallbekken 2010; Michaelow et al. 2010; Farber de Anda et al. 2010; Finley and Schuchard 2011; Koptko and Perkins 2010; Mehta et al. 2011; Linnerud et al. 2011; Urban and Mitchell 2022; Ebinjer and Vergara 2011; Willbanks et al. 2012; Schaeffer et al. 2012; Sathaye et al. 2012; van Vliet et al. 2012; Goldman et al. 2012; Sieber 2013; Klein et al. 2013; NYC 2013; Zamuda et al. 2013; Nierop 2014; de Bremond et al. 2014; Audinet et al. 2014; Bartos and Chester 2015; DOE 2015
Address extreme weather and environmental threats	30 (91%) papers	Ball 2006; Coughlin and Goldman 2008; Vine 2008; Acclimatise 2009; Koch et al. 2009; Perez 2009;Mideksa and Kallbekken 2010; Farber de Anda et al. 2010; Michaelow et al. 2010; Koptko and Perkins 2010; Beard et al. 2010; Mehta et al. 2011; Finley and Schuchard 2011; Urban and Mitchell 2011;Ebinjer and Vergara 2011; Willbanks et al. 2012;Schaeffer et al. 2012; Sathaye et al. 2012; van Vliet et al. 2012; Caring for Climate 2012; Goldman et al. 2012; Sieber 2013; Klein et al. 2013; NYC 2013; Zamuda et al. 2013; Nierop 2014; de Bremond et al. 2014; Audinet et al. 2014; Bartos and Chester 2015; DOE 2015
Address specific threats on electric infrastructure	23 (70%) papers	Ball 2006; Coughlin and Goldman 2008; Vine 2008; Acclimatise 2009; Perez 2009; Beard et al. 2010; Michaelow et al. 2010; Farber de Anda et al. 2010; Koptko and Perkins 2010; Finley and Schuchard 2011; Urban and Mitchell 2011; Ebinjer and Vergara 2011; Willbanks et al. 2012; Schaeffer et al. 2012; Sathaye et al. 2012; Goldman et al. 2012; Sieber 2013; NYC 2013; Zamuda et al. 2013; Nierop 2014; de Bremond et al. 2014; Audinet et al. 2014; DOE 2015
Focused on research levels based on mid- to long-term climate	20 (61%) papers	Breslow and Sailor 2002; Coughlin and Goldman 2008; Acclimatise 2009; Koch et al. 2009; Perez 2009; Mideksa and Kallbekken 2010; Beard et al. 2010; Koptko and Perkins 2010; Schaeffer et al.

projections		2012; Mehta et al. 2011; Ebinjer and Vergara 2011; Willbanks et al. 2012; Sathaye et al. 2012; van Vliet et al. 2012; Goldman et al. 2012; Klein et al. 2013; Zamuda et al. 2013; Audinet et al. 2014; Bartos and Chester 2015; DOE 2015
Outline a climate assessment methodology	25 (76%) papers	Breslow and Sailor 2002; Coughlin and Goldman 2008; CERES et al. 2008; Finley and Schuschard 2011; Koch et al. 2009; Acclimatise 2009; Perez 2009; Michaelow et al. 2010; Farber de Anda et al. 2010; Koptko and Perkins 2010; Mehta et al. 2011; Linnerud et al. 2011; Urban and Mitchell 2022; Ebinjer and Vergara 2011; Willbanks et al. 2012; Schaeffer et al. 2012; Sathaye et al. 2012; van Vliet et al. 2012; Caring for Climate 2012; Klein et al. 2013; Zamuda et al. 2013; de Bremond et al. 2014; Audinet et al. 2014; Bartos and Chester 2015; DOE 2015
Address stakeholder engagement or cross-collaboration	11 (33%) papers	CERES et al. 2008; Coughlin and Goldman 2008; Acclimatise 2009; Michaelowa et al 2010; Mehta et al 2011; Finley and Schuchard 2011; Schaeffer et al. 2012; Zamuda et al 2013; Nierop 2014; de Bremond et al. 2014; DOE 2015
Discuss potential adaptation actions	30 (91%) papers	Ball 2006; Coughlin and Goldman 2008; CERES et al. 2008; Vine 2008; Koch et al. 2009; Acclimatise 2009; Perez 2009; Mideksa and Kallbekken 2010; Michaelow et al. 2010; Farber de Anda et al. 2010; Koptko and Perkins 2010; Finlet and Schuchard 2011; Mehta et al. 2011; Linnerud et al. 2011; Urban and Mitchell 2022; Ebinjer and Vergara 2011; Willbanks et al. 2012; Schaeffer et al. 2012; Sathaye et al. 2012; van Vliet et al. 2012; Caring for Climate 2012; Goldman et al. 2012; Sieber 2013; NYC 2013; Zamuda et al. 2013; Nierop 2014; de Bremond et al. 2014; Audinet et al. 2014; Bartos and Chester 2015; DOE 2015

Highlights

- The electric utility industry is an important player in the climate change arena
- There is diversity in the types of adaptation actions, methods for measuring risk, and mechanisms for engaging stakeholders in climate risk management in the electric utility industry
- There is significant emphasis on the identification of potential climate change impacts and opportunities for adaptation in climate risk management in the electric utility industry
- We find less attention has been paid to assessments of risk, stakeholder engagement, and cross-sectoral collaboration in climate risk management