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Climate risk assessment and cascading impacts: Risks and opportunities for an electrical utility in the U.S. Southwest

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ABSTRACT

Climate risks pose a particular set of challenges to electrical utilities, who must manage the direct impacts of climate and weather, as well as how related effects might propagate through networks of interconnected social and environmental risks. In this paper, we present a case study example of climate services development, co-produced between a regional electrical utility and researchers at the University of Arizona, that integrates and adapts a climate risk management framework to better connect university climate expertise with utility needs for climate risk management and planning. We detail the process by which our project team partnered with the utility to identify primary areas of concern for the electrical utility sector in the Southwest, and craft a qualitative assessment of these climate risks with the utility. We describe the iterative engagement process where operational implications associated with climate risks were identified including points of intervention for the utility, as part of their integrated resource planning process, and the cascading impacts that play a part in the larger decision context. We emphasize the role of novel analyses and curated data and information in the development of tailored climate services, as well as the importance of cultivating collaborative relationships between university researchers and community stakeholders and practitioners early on in research projects in order to better include their values, perspectives, and insights in the research process.

1. Introduction & background

Utility infrastructure such as generating stations, solar fields and arrays, and transmission and distribution lines, is capital-intensive, immobile, and critical to utility operations. This infrastructure is directly vulnerable to extreme weather events and climate change (Sathaye et al., 2011; Yates et al., 2014; U.S.-DOE, 2013), but is also engineered to withstand the local environment, such as the hot and arid conditions of the Southwest (Gerlak and McMahan, 2017). A warming climate with longer summers, however, could reduce the efficiency of generating resources, transmission lines, or renewables, and could eventually exceed the optimal operating temperatures for critical infrastructure (Bartos and Chester, 2015; Office of Energy Policy and System Analysis, 2015). Increased daily average and maximum temperatures, overnight low temperatures, and cooling degree days, along with prolonged and

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extreme heat waves, will also increase use of interior climate control, resulting in higher daily/peak load and longer seasonal periods of use (Zamuda et al., 2018; Mideksa and Kallbekken, 2010). Population growth within, and demographic movement into the Sun Belt will intensify demand for utility services during elongated warm seasons (cf. Isaac and van Vuuren, 2009). In addition, power plants in the Southwest face water shortages and reduced generating capacity, based on projections for decreased average and summer precipitation, intensified droughts, and declining or altered streamflow in major river basins (Office of Energy Policy and System Analysis, 2015; Bartos and Chester, 2015). Overallocation of water in the U.S. Southwest will likely lead to increased competition over access-to and use-of these resources in the near future and beyond, as tribal, municipal, agricultural, commercial, and industrial uses all vie for an increasingly limited resource (U.S.-BOR, 2012), with potential amplification of this risk under climate change scenarios (Barnett and Pierce, 2009).

Climate change, the persistence of drought, and increased demand for utility services may appear less urgent until critical thresholds are breached, especially compared to extreme events and emergency management of acute events such as rolling power outages or damaged infrastructure from acute events such as wildfire. Emergent scholarship reveals the potential for extreme events with cascading impacts and serious consequences – sometimes identified as high-impact, low-probability events (Garfin et al., 2016). Management and planning for these scenarios must grapple with the balance between the probability and the severity of a given event, not to mention the relationships between events on both short- and long-term timescales. Utility sector research has placed comparatively less focus on adaptation and long-term resilience to climate risk in the energy sector (Gerlak et al., 2018). A climate risk management (CRM) framework (e.g., Travis and Bates, 2014; Gerlak et al., 2018) provides a novel way to conceptualize long term planning that anticipates future climatic conditions, and is resilient to changes in baseline conditions and the destabilizing effects of extreme events. This approach emphasizes careful assessment of what is known about a set of plausible outcomes, including the current state of knowledge, and what could realistically be enacted to help mitigate the risks associated with those outcomes.

The World Meteorological Organization’s Global Framework for Climate Services (GFCS) and the rise of both public and private sector climate service providers on regional, national, and international scales reflect the growing use and relevance of climate services (Georgeson et al., 2017; Gerlak and Greene, 2019). Development and dissemination of climate services requires innovative structures that can coordinate working connections between institutions, projects, and financial resources; and this increasingly includes private sector services to fill the gap (Hewitt et al., 2012). Climate risk management incorporates climate impacts, forecasts, and projections into decision making to increase or maintain benefits and reduce potential harm or losses (Kunreuther et al., 2013; Travis and Bates, 2014). It extends from assessing problems and identifying solutions to climate change impacts that integrates multiple perspectives (cf. Hellmuth et al., 2007), such as applied climatology (Svoboda et al., 2015), social science (Crate, 2011), and business and climate risk management (Pattberg, 2012). A climate risk management approach is enhanced by collaborations between university researchers and partners (Austin, 2004; Brasseur and Gallardo, 2016), especially where jointly defined questions and frequent interactions produce practical, or actionable science (Moss et al., 2013; Meadow et al., 2015), and which can further develop risk assessment methods and promote a broad suite of technological, behavioral, and institutional practices necessary for greater resilience (Audinet et al., 2014).

Risk and decision analyses incorporating the uncertainty of events and their consequences can lead to the discovery of optimal, efficient, or at least satisfactory decisions for realistic and nuanced outcomes, as opposed to a reductive, singular “best” answer, and includes connections-to and impacts-on the social institutions, economic interests, and environmental processes that shape these risks (Travis and Bates, 2014; Kettle et al., 2014). Cascading environmental impacts illustrate primary and secondary risks to utilities. For example, development into the wildland-urban interface has increased wildfire risk, a risk already magnified by climate change, while suburban growth and development also place greater demand on utilities in terms of demographic pressure. The increased demand in a warming climate and the increased vulnerability of transmission and distribution systems to wildfire, highlight the overlapping consequences of damaged infrastructure or disrupted utility operations. This amplifying sense of risk is endemic to many “wicked” problems (Head, 2008), and further illustrates the need to fully explore the context of vulnerability, risk, and adaptation (De Bremond et al., 2014).

A climate risk management framework also highlights the risks and opportunities associated with adaptation and mitigation of climate variability, extreme weather, and climate change. Electrical utilities have specific concerns given the challenge of sustainable operations given persistent environmental conditions and punctuated extreme events. Reports from the Intergovernmental Panel on Climate Change (IPCC) and National Climate Assessment (NCA) provide a roadmap for anticipated future conditions and highlight the need to include these changes in short and longer-term planning. These reports are not necessarily designed for the day-to-day operations of a utility, however, and they lack specific guidance for the particularities of local-to-regional decision making where utilities operate. This leaves utilities in the position of possessing an increasing awareness of the need to act, but often lacking specific operational information that would inform decision making at scales and timelines relevant to their needs. The applied climate science community has embraced the need to include stakeholders and practitioners in collaborative research, often through the lens of boundary organizations – bridging groups that connect science and decision making, or co-production – authentic collaboration that blurs the line between scientist and practitioner, and breaks down barriers by recognizing that expertise and capacity is distributed across multiple disciplines and located within and outside the academic community (i.e. in the private sector, government, NGOs, etc.). As these relationships evolve and develop, attempts to better characterize the nature of these interactions (see Meadow et al., 2015) and how this relates to climate services development (see Bremer and Meisch, 2017) raise important questions about these interactions.

This paper presents a case study example of a climate risk assessment, co-produced as part of a research collaboration between the University of Arizona (UArizona) and Tucson Electric Power (TEP), Tucson’s utility. Our case study describes the process by which we developed and revised a climate risk assessment focused on areas of concern specific to TEP operations and informed by ongoing interactions with TEP collaborators over the course of the project. We discuss the social and environmental contexts in which these plans and decisions are embedded, including interrelated effects and cascading impacts that play a part in the larger decision context. We also consider the scalability and transferability of this process, in terms of relevance and applicability to other utilities or private sector entities in a business risk management framework. Finally, we reflect on how a relationship-based approach relates to theories-about and strategies-for climate services development, and how this connects to collaborative research frameworks and university/community research partnerships.

2. Collaborative process and methods

In the following section, we briefly describe the development of the partnership between UArizona and TEP, we outline our process of co-producing a risk assessment that identified climate risks and areas of concern where additional information would be needed to make more informed planning decisions, and we summarize the initial climate risk assessment that fed into subsequent analyses of what these risks meant for TEP, and the relationships and cascading impacts between interconnected social and environmental factors. This section focuses on a summary of the framing and methods from our technical report on this project, written in collaboration with our UArizona team and presented to TEP at the conclusion of that project. For more details on the process, readers should consult Gerlak and McMahan (2017).

2.1. Initial engagement with a utility partner

The Arizona Business Resilience Initiative (ABRI) was launched at the University of Arizona in 2015, under the direction of the university's Vice President for Research. The university was interested in supporting partnerships with regional business entities, and ABRI was designed to develop a project framework that could help enhance businesses' ability to react and respond to climate risks. Project leaders at UArizona elected to partner with Tucson's regional electrical utility – TEP– based on their concern over risks associated with climate variability and climate change, and the relevance of utilities to long term regional sustainability. Like most utilities, TEP is finding it increasingly necessary to plan-for and respond-to environmental, legislative, and economic drivers related to climate change, and in 2015, they were exploring how they could adjust their energy portfolio to respond to regulatory elements embedded within the U.S. Environmental Protection Agency's (U.S. EPA) Clean Power Plan (CPP),[1] and to anticipate potential future climate and regulatory contexts that might affect their decision-making and planning.

The UArizona team provided data and information about local conditions and climate change projections, discussed the trend of warmer temperatures and elongated summers, and reviewed examples of other businesses that had used climate information in their long-term planning (Sussman and Freed, 2008; UN, 2012). The reported trend of warmer and longer summers that blur into spring and fall highlighted potentially adverse impacts as well as increased demand for utility services, which could also point towards increased revenue. From a business risk management perspective, a 'risks and opportunities' framing was a more appropriate tack, and rather than pursuing a traditional consultative relationship focused on discrete deliverables, the UArizona ABRI team shifted the project to operate in a collaborative manner, that was learning from the process of developing the climate risk management assessment, in addition to providing specific information to TEP based on the values that shape and influence their decision-making priorities (Aalst et al., 2008; O'Brien and Wolf, 2010; Howden and Jacobs, 2016). This included an examination of the types of data and information TEP currently uses, and priority areas where they would benefit from additional or more detailed information. Early discussions also included TEP educating the ABRI team about the planning processes at the utility, how data and information are integrated into the integrated resource plan (IRP), and the relevant time scales for their decision-making processes.

2.2. Co-producing a risk assessment

We identified four climate risk areas that represented known areas of concern or areas where additional information would be needed to make a more informed planning decision. These include: (1) Climate Extremes and Heat; (2) Wildfire and Associated Complications; (3) Air Quality and Pollution; and (4) Water Availability. Researchers summarized the results of these initial discussions in a matrix in order to conceptualize the intensity and timing of the various risks, and to assess how these risks might affect planning and policy on three different timescales (Fig. 1). This was a modification of a standard risk assessment matrix that categorizes risks based on their probability and their severity or impact. This was a starting point for what was known, as well as priority areas to explore, and helped us identify relevant timescales, along with gaps in our shared understanding and why these gaps were important.

Project leaders recruited additional researchers from UArizona to assess and prioritize climate risks for TEP specific to each of these four subject areas, as well as how these risks might overlap. Serial meetings between UArizona researchers and relevant TEP personnel provided an opportunity for the UArizona teams to summarize existing data and their connection to initial concerns expressed by TEP. This process identified the primary areas of impact where climate was likely to affect TEP planning and decision making (Fig. 2). UArizona teams focused on these four subject areas (Heat/Climate, Wildfire, Water Availability, and Air Quality), and synthesized primary and secondary research on each of these four risk areas (see Gerlak and McMahan, 2017). We also produced an updated climate risk assessment matrix that characterized the timescale and severity of the risks, their relative probability, and the confidence/

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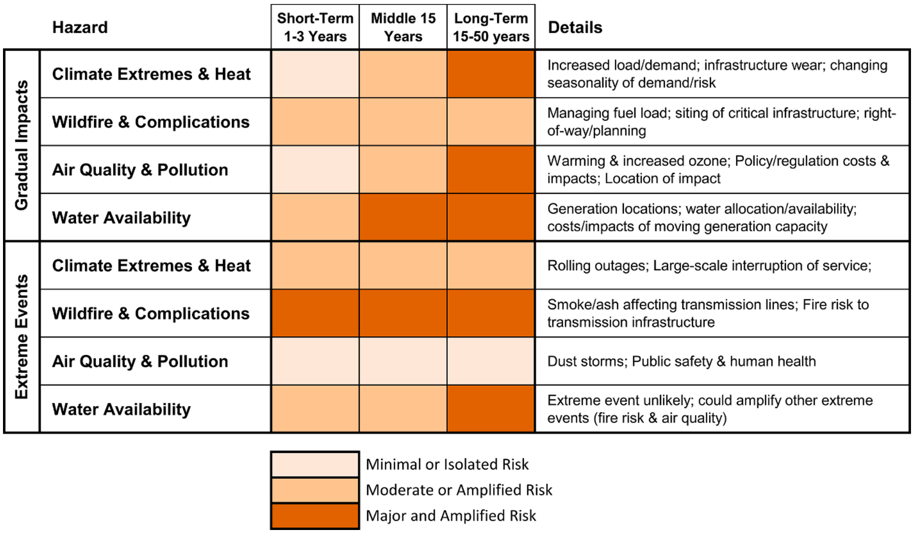
[1] Although the Trump Administration issued an executive order terminating the CPP in March 2017, many western states are continuing to make plans to reduce greenhouse gas emissions. Some states (like California and Colorado) are leading the way with ambitious renewable energy mandates. Of the western states, Arizona has the least stringent renewable energy mandate at 15% by 2025 (Shogren, 2017).



	Hazard	Short-Term 1-3 Years	Middle 15 Years	Long-Term 15-50 years	Details
Gradual Impacts	Climate Extremes & Heat	░	▒	█	Increased load/demand; infrastructure wear; changing seasonality of demand/risk
	Wildfire & Complications	▒	▒	▒	Managing fuel load; siting of critical infrastructure; right-of-way/planning
	Air Quality & Pollution	░	▒	█	Warming & increased ozone; Policy/regulation costs & impacts; Location of impact
	Water Availability	▒	█	█	Generation locations; water allocation/availability; costs/impacts of moving generation capacity
Extreme Events	Climate Extremes & Heat	▒	▒	▒	Rolling outages; Large-scale interruption of service;
	Wildfire & Complications	█	█	█	Smoke/ash affecting transmission lines; Fire risk to transmission infrastructure
	Air Quality & Pollution	░	░	░	Dust storms; Public safety & human health
	Water Availability	▒	▒	█	Extreme event unlikely; could amplify other extreme events (fire risk & air quality)

░ Minimal or Isolated Risk
▒ Moderate or Amplified Risk
█ Major and Amplified Risk

Fig. 1. Initial risk and scale of impact matrix.

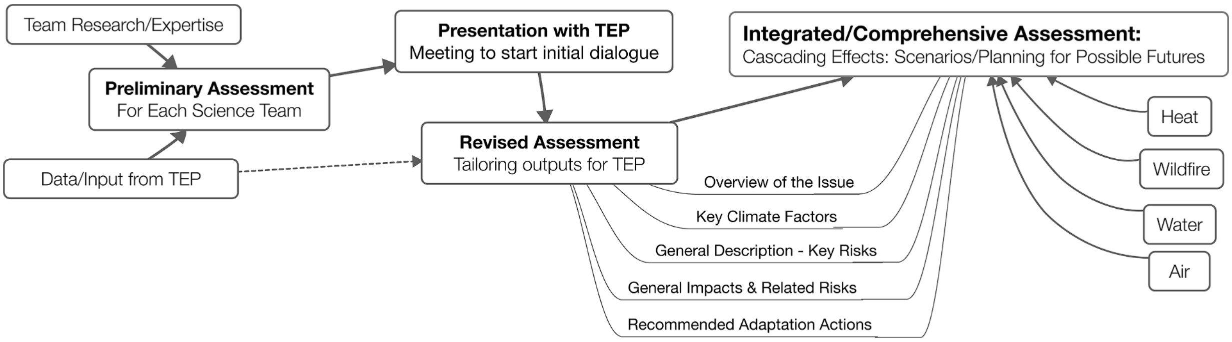


Fig. 2. Project framework and iterative process.

uncertainty of data about each risk. The matrix also included an assessment of the intervention potential for each risk, as well as a summary of the level of expressed concern about each risk (coded as “perception”). UArizona ABRI team members coded these data to create additional visualizations that identified areas where TEP had opportunities for climate risk adaptation or mitigation, and other areas where there were fewer opportunities to drive climate risk management and adaptation. The UArizona team developed diagrams to visualize cascading impacts that spanned across networks of interrelated phenomena, including social factors (e.g. demographic change, commercial development, etc.) and environmental conditions (e.g. baseline climate, seasonal and decadal variability, El Niño and La Niña, the SW Monsoon, etc.), that could alter calculations of risks and management of impacts.

3. Key risk assessment findings

In the following section, we provide a brief summary of findings from the risk assessment organized around the four thematic areas, an updated risk matrix that summarizes our qualitative risk assessment of the four thematic areas, and an overview of our analysis of the cascading impacts that describe the relationships between social and environmental factors for each of the four thematic areas. This information and these results are derived from the technical report for this project. For more detailed results, including information about our process and outcomes, the role and contributions of the UArizona and TEP collaborators, and the context and sources for these sectoral summaries, please refer to Gerlak and McMahan (2017).

3.1. Key risks in four thematic areas

3.1.1. Wildfire

Transmission lines connecting remote generation systems to regional utility grid networks are vulnerable to increased wildfire activity. Wildfires can cause physical damage to structures, conductors, and other related equipment, and heat, smoke, and particulate matter can impact the capacity of transmission lines, or even cause arcing between lines if soot accumulates on the insulators and ionized air in the smoke can act as conductor, causing protective equipment to shut a line down, resulting in planned or unplanned outages. Outages can also result from emergency line de-rating or shut-downs during a nearby fire in order to prevent thermal damage to the line, to prevent a smoke-caused trip, or to meet the safety needs of firefighters. Buffelgrass (*Pennisetum ciliare*) is a rapidly spreading invasive species that increases fire risk and tends to migrate into disturbed areas and transmission lines are often located in disturbed areas due to the removal of fuel loads. The fire season is lengthening in the Southwest under current climate conditions (Abatzoglou and Williams, 2016). The seasonality of vegetation growth responds to inter and intra-annual variability, with seasonal and annual fluctuations in precipitation and temperatures that encourage vegetation growth. Following fire, de-vegetated landscapes are more unstable and susceptible to landslides, and the resulting debris flow poses a critical threat to infrastructure. Post-fire flooding is of heightened concern in mountainous areas of the Southwest that experience monsoon rain events immediately following the late-spring fire season.

3.1.2. *Heat*

In the Southwest, the warm season is characterized by sustained high temperatures starting in the spring, continuing through the summer, and extending well into fall. Utilities plan for increased demand associated with summertime heat by assessing daily peak load and seasonal demand in order to incorporate plausible scenarios for daily and seasonal patterns into long-term projections and seasonal forecasting. Extreme heat wave events can cause spikes in demand that increase pressure on regional energy supply/markets and can affect the efficiency and stability of regional distribution systems. These events can also cause additional complications if the electrical distribution network fails causing either a local outage or regional blackout. Heat wave events and sustained extreme temperatures affect demand on regional energy production and distribution systems, including the market availability and price of energy during times of high regional demand. These events can also exacerbate disruptions ranging in scale and intensity from minor neighborhood blackouts of limited duration, to widespread events that can cause much more dangerous or catastrophic outcomes. Increased nighttime temperatures will prevent equipment from cooling off and high daytime temperatures may overload equipment causing them to overheat and shortening equipment lifespans. Warming temperatures will also lead to increased revenue during transitional seasonal periods (i.e. spring and fall) when electrical demand has historically been lower but increased regional demand may also increase market competition (and price) for generating resources during this time.

3.1.3. *Water*

Water availability and competition sits at the intersection of climate projections and projected demand and sourcing (i.e. surface vs groundwater), water rights and competition over different uses (especially around large municipal areas), and regulatory frameworks (e.g. Active Management Areas (AMAs)) (Jacobs and Holway, 2004). Changes in snowpack dynamics that impact surface water and groundwater recharge could have significant impacts on future water availability. The regional generating portfolio in the Southwest includes thermoelectric power plants within the regional watershed that depend on water resources for cooling, and decreased availability of water could increase operational costs and the cost of power produced. As portfolios are shifted from coal powered generation in the four corners region to natural gas -powered generation in the Phoenix region, this moves water consumption from the Arizona Mountain Plateau to the Desert Basin region, with different regulatory and physical risks for the natural gas generating stations located in central Arizona (located in the Phoenix AMA, the Pinal AMA, the Harquahala Irrigation Non-Expansion Area (INA), and the Gila groundwater basin). Groundwater Code regulations protect the availability of groundwater in the AMAs for municipal and industrial use, particularly in the Phoenix and Tucson AMAs (Pinal AMA and Harquahala INA have less restrictive management goals), so the most advantageous place to be located from a groundwater perspective is in the highly-regulated basins. Due to the complex multi-state legal management scheme of the Colorado River, electricity production that depends directly on hydroelectric plants or water supplies from mainstream reservoirs may have different impacts from the Central Arizona Project (CAP) itself. However, if main stem reservoir levels continue to decline, ongoing negotiations across the basin states could affect power production capacity as well as demand for power in multiple ways that may be hard to anticipate.

3.1.4. *Air*

The ongoing shift from coal fired generating capacity in the four corners region to natural gas generating units in Southern Arizona highlights a key issue for metropolitan areas, namely U.S. EPA O_3 non-attainment status, and the role that new generating units might play in increased NO_x emissions and surface level O_3 formation. From a utility perspective, NO_x/O_3 is primarily a point source concern related to power generating stations they either own or have included in their regional power resource portfolio. Generating stations produce a small percentage of the total NOx and VOC load compared to those produced by automotive transportation and freight (e.g. personal vehicles and semi freight hauling). The CPP introduced uncertainty into utility management and planning by including carbon emissions in the regulatory framework under which utilities and power generating companies operate. There have been recent shifts away from coal fired generating capacity, partly as a result of increased emissions regulation associated with coal fired generating capacity (when the CPP was still in place), but mostly because of market conditions. Aside from any regulatory or environmental framework, the price of natural gas has caused many utilities to reconsider their resource portfolio and leasing strategies, where natural gas and renewables provide price competitive options for generating capacity in comparison to coal, and without the possible implications of a reinstated U.S. EPA CPP.

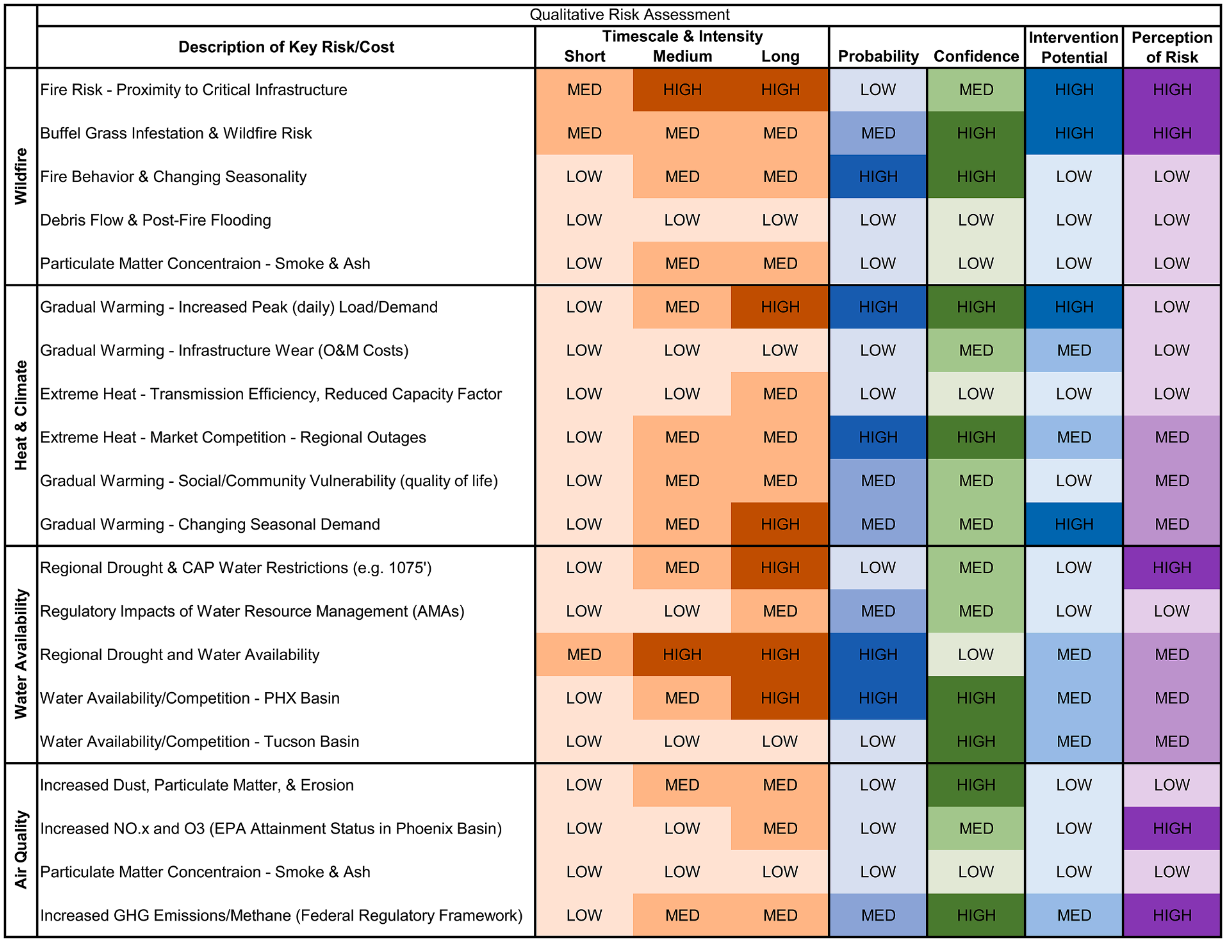
3.2. *Qualitative risk assessment matrix*

The risk assessment matrix (Fig. 3) synthesized our shared understanding of risks and opportunities across the four thematic areas of concern and highlighted a few crucial patterns. First, this matrix identified areas of known risk, sometimes extreme, but where the actual probability of an occurrence is low (e.g. wildfire and vulnerable infrastructure). In other cases, the probability is low, but represents an area of ongoing concern for TEP, so any updated information would help them monitor these risks (e.g. water resource management). Second, the process of developing the risk matrix identified high impact risks with an elevated probability of occurrence, and where TEP had a realistic opportunity to intervene or inform TEP policy and practice (e.g. critical infrastructure right of way fuel load management, planning for increased utility demand in future summers). Finally, this assessment highlighted areas where risks were low, despite elevated levels of concern (high perception rank), and where the results of the assessments identified risks that were unlikely to require intervention based on utility concerns (e.g. air quality and NOx and O3 management in the Phoenix metropolitan area).

A comparison of probability vs impact demonstrates where each of the identified risks falls, and highlights clusters of concerns both more likely to occur, and more likely to have an impact on utility operations (Fig. 4). This does little to accommodate for risks that could actually be intervened upon. A combination of probability and impact in a single category in comparison to the intervention potential highlights areas that are of increased concern given their probability and impact, but which have realistic paths to intervention on the part on the utility (Fig. 5). Particularly notable are concerns about greenhouse gas emissions and federal regulatory frameworks, as well as emergent efforts to reduce or eliminate carbon emissions from power generation portfolios at TEP and in the utility industry more broadly.

3.3. *Cascading impacts: Synthesizing across the qualitative risk assessment*

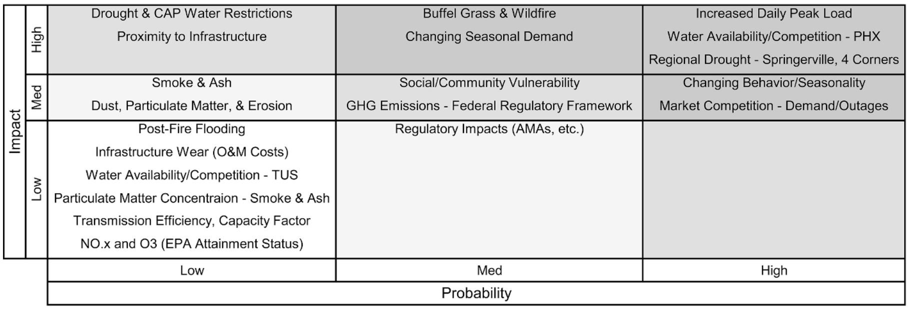
The four climate risk areas demonstrate overlap between environmental phenomena, intersections that amplify impacts of each risk area. The social and environmental contexts of these relationships, as well as the risk areas themselves, highlight the role of climate risk management in addressing short term (acute) exposure, and the long-term (chronic) risks, as well as what this information means for planning and decision making. For each topical cluster, three inputs within the ‘social and environmental context’ were identified: (1) *Background Climate* – the climatic and environmental conditions that serve as a baseline for climate risk assessments (in yellow); (2)



Qualitative Risk Assessment

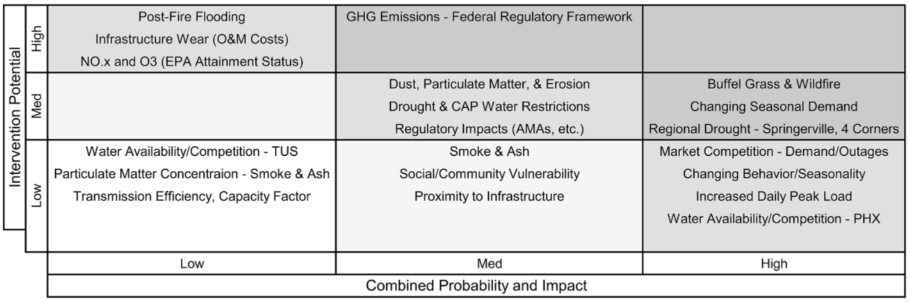
	Description of Key Risk/Cost	**Timescale & Intensity**			**Probability**	**Confidence**	**Intervention Potential**	**Perception of Risk**
		Short	**Medium**	**Long**				
Wildfire	Fire Risk - Proximity to Critical Infrastructure	MED	HIGH	HIGH	LOW	MED	HIGH	HIGH
	Buffel Grass Infestation & Wildfire Risk	MED	MED	MED	MED	HIGH	HIGH	HIGH
	Fire Behavior & Changing Seasonality	LOW	MED	MED	HIGH	HIGH	LOW	LOW
	Debris Flow & Post-Fire Flooding	LOW	LOW	LOW	LOW	LOW	LOW	LOW
	Particulate Matter Concentraion - Smoke & Ash	LOW	MED	MED	LOW	LOW	LOW	LOW
Heat & Climate	Gradual Warming - Increased Peak (daily) Load/Demand	LOW	MED	HIGH	HIGH	HIGH	HIGH	LOW
	Gradual Warming - Infrastructure Wear (O&M Costs)	LOW	LOW	LOW	LOW	MED	MED	LOW
	Extreme Heat - Transmission Efficiency, Reduced Capacity Factor	LOW	LOW	MED	LOW	LOW	LOW	LOW
	Extreme Heat - Market Competition - Regional Outages	LOW	MED	MED	HIGH	HIGH	MED	MED
	Gradual Warming - Social/Community Vulnerability (quality of life)	LOW	MED	MED	MED	MED	LOW	MED
	Gradual Warming - Changing Seasonal Demand	LOW	MED	HIGH	MED	MED	HIGH	MED
Water Availability	Regional Drought & CAP Water Restrictions (e.g. 1075')	LOW	MED	HIGH	LOW	MED	LOW	HIGH
	Regulatory Impacts of Water Resource Management (AMAs)	LOW	LOW	MED	MED	MED	LOW	LOW
	Regional Drought and Water Availability	MED	HIGH	HIGH	HIGH	LOW	MED	MED
	Water Availability/Competition - PHX Basin	LOW	MED	HIGH	HIGH	HIGH	MED	MED
	Water Availability/Competition - Tucson Basin	LOW	LOW	LOW	LOW	HIGH	MED	MED
Air Quality	Increased Dust, Particulate Matter, & Erosion	LOW	MED	MED	LOW	HIGH	LOW	LOW
	Increased NO.x and O3 (EPA Attainment Status in Phoenix Basin)	LOW	LOW	MED	LOW	MED	LOW	HIGH
	Particulate Matter Concentraion - Smoke & Ash	LOW	LOW	LOW	LOW	LOW	LOW	LOW
	Increased GHG Emissions/Methane (Federal Regulatory Framework)	LOW	MED	MED	MED	HIGH	MED	HIGH

Fig. 3. Qualitative risk assessment matrix.



		Probability		
		Low	Med	High
Impact	High	Drought & CAP Water Restrictions Proximity to Infrastructure	Buffel Grass & Wildfire Changing Seasonal Demand	Increased Daily Peak Load Water Availability/Competition - PHX Regional Drought - Springerville, 4 Corners
	Med	Smoke & Ash Dust, Particulate Matter, & Erosion	Social/Community Vulnerability GHG Emissions - Federal Regulatory Framework	Changing Behavior/Seasonality Market Competition - Demand/Outages
	Low	Post-Fire Flooding Infrastructure Wear (O&M Costs) Water Availability/Competition - TUS Particulate Matter Concentraion - Smoke & Ash Transmission Efficiency, Capacity Factor NO.x and O3 (EPA Attainment Status)	Regulatory Impacts (AMAs, etc.)	

Fig. 4. Probability vs impact – qualitative assessment of risks and opportunities.



		Combined Probability and Impact		
		Low	Med	High
Intervention Potential	High	Post-Fire Flooding Infrastructure Wear (O&M Costs) NO.x and O3 (EPA Attainment Status)	GHG Emissions - Federal Regulatory Framework	
	Med		Dust, Particulate Matter, & Erosion Drought & CAP Water Restrictions Regulatory Impacts (AMAs, etc.)	Buffel Grass & Wildfire Changing Seasonal Demand Regional Drought - Springerville, 4 Corners
	Low	Water Availability/Competition - TUS Particulate Matter Concentraion - Smoke & Ash Transmission Efficiency, Capacity Factor	Smoke & Ash Social/Community Vulnerability Proximity to Infrastructure	Market Competition - Demand/Outages Changing Behavior/Seasonality Increased Daily Peak Load Water Availability/Competition - PHX

Fig. 5. Scale of impact vs intervention potential of risk.

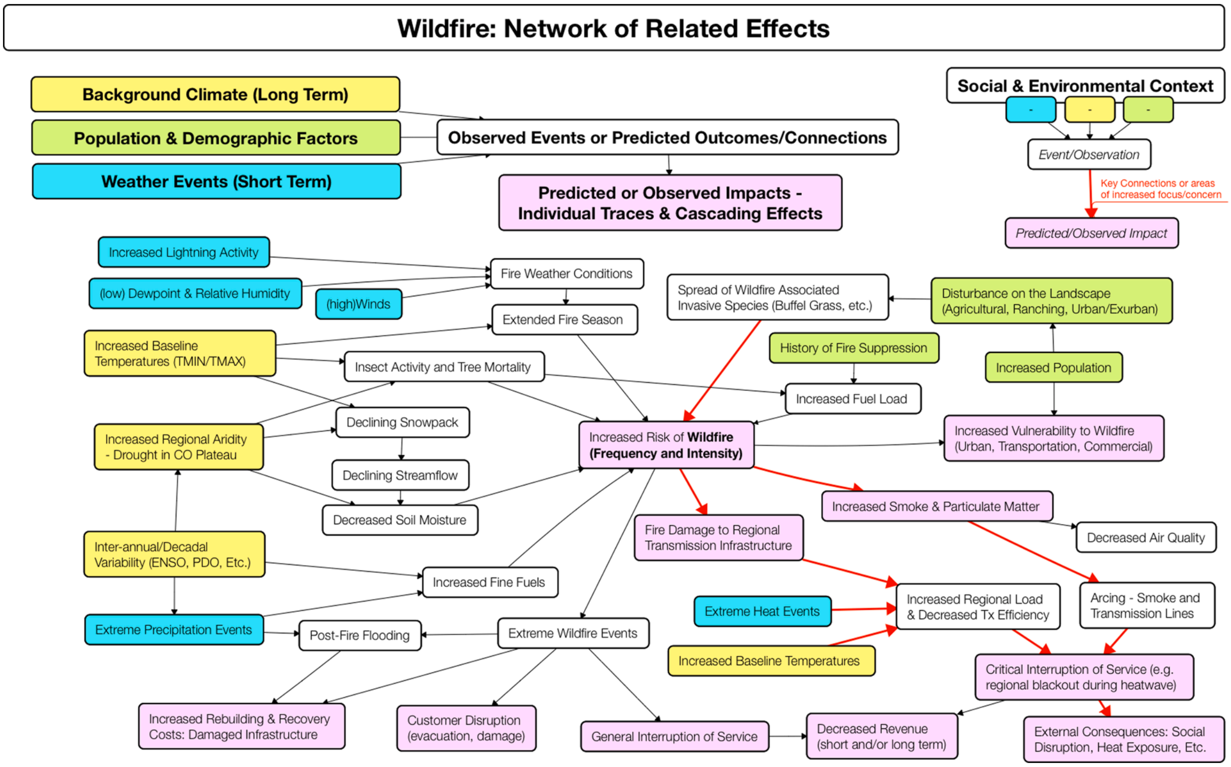


Fig. 6. Example of interconnected utility risks diagram – wildfire.

Population and Demographic Factors – the social conditions that can alter the context or implications for a given environmental risk (in green); and (3) *Weather Events* – the short-term fluctuation around climatic patterns that generally fall within a range of expected values but are difficult to predict more than 7–10 days in advance (in blue). This categorization distinguished between long term impacts necessitating strategic resource planning by the utility, and acute events with short term impacts that increase operational vulnerability.

We coordinated among our UA research team and worked with TEP to define the network of interrelated effects to identify connections and cascading impacts between the aforementioned inputs to this social and environmental context (climate, demographic, and weather). The connecting lines indicate a relationship that we identified as part of this process, and the arrow indicates the directionality of this relationship. We used this process to identify the relationship between observed events or predicted outcomes (in white) and their connection to some of the most likely predicted or observed impacts (in purple). As part of this process, we also highlighted plausible scenarios of concern for cascading impacts within these networks, identified with orange lines in the diagrams. These orange lines highlight pathways of known concern, or areas which require additional focus given the potential for acute events or cascading impacts (see Figs. 6–9 for the resulting conceptual model for each thematic area from this analysis).

This analysis highlights three observations related to the cascading impacts associated with the climate risks. First, we observe that there are ***implications associated with specific courses of action***. Decision points informed by novel data and information, including links to policy, regulations, risks and impacts, as well as better defining areas where this new data and information reveal a lack of risk. Competition over limited water resources is an important factor to consider in both the short term and longer-term planning horizons. Current movement away from coal fired generation in the four corners region of the Southwest is taking place within shifts in environmental regulatory frameworks (e.g. the U.S. EPA and CPP), and while U.S. EPA plans are on hold pending further review, these types of regulatory costs and limitations may occur in the future. The risks, costs, and benefits associated with investment in these resources (as well as the risks, costs, and benefits of moving away from these investments) is a key part of climate risk management decision making in response to these risks, and that leverages emergent market opportunities.

A shift from coal-fired generation is occurring within the context of a move towards natural gas generation, but at facilities located in closer proximity to metropolitan areas in the Southwest. Water is a key part of cooling generating resources, but as populations grow, increasing competition over water resources will place additional pressure on decisions about investments in infrastructure. Another consideration is potential future regulation of NOx and O_3 attainment status, with concerns over the role that regional gas-powered power plants might play in producing these pollutants or their precursors. Even though natural gas generation has been documented as making small contributions to the overall NOx/O_3 levels in the Phoenix basin (cf. Li et al., 2015; Gerlak and McMahan, 2017), these generating stations are a visible point source for these compounds, and beyond their contributions to regional air quality, it remains important to monitor changes in regulatory frameworks, as well as public attention paid to these risks.

Second, our assessment reveals the value of information about the ***impact of future environmental conditions,*** and how the current and future climate will affect decision-making on multiple timescales. Increased intensity and duration of summer temperatures may

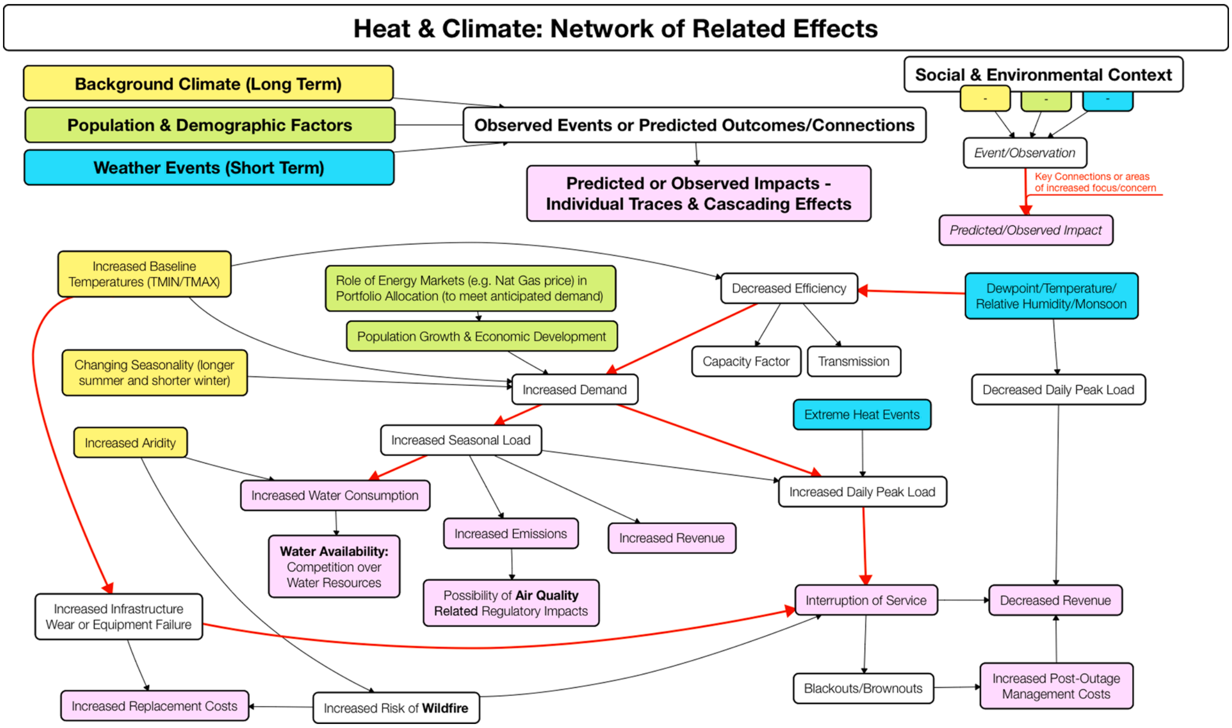


Fig. 7. Example of interconnected utility risks diagram – extreme heat & climate change.

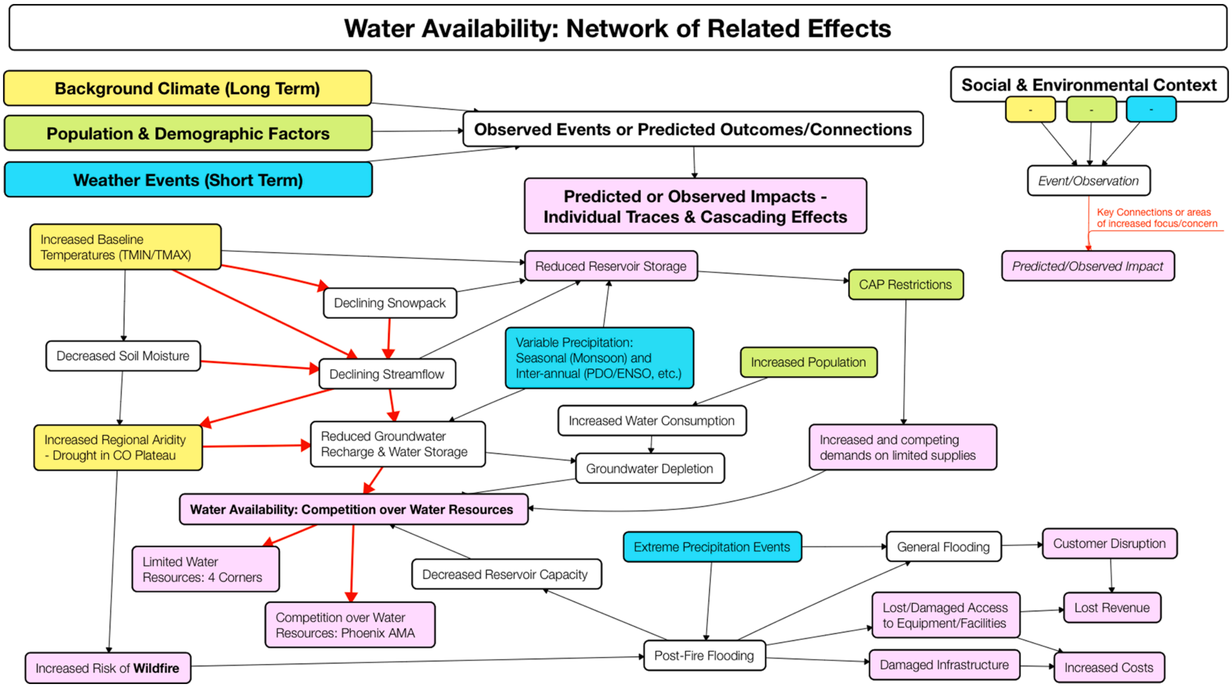


Fig. 8. Example of interconnected utility risks diagram – water availability.

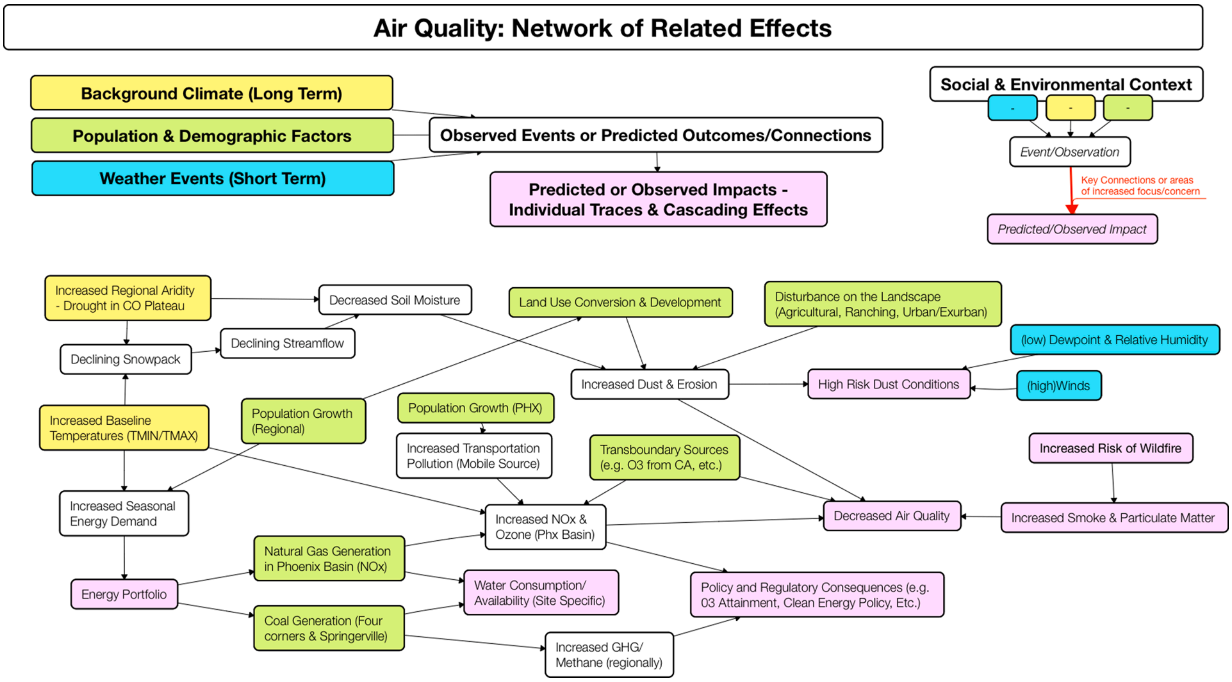


Fig. 9. . Example of interconnected utility risks diagram – air quality.

result in increased utility revenue, but there are short-term concerns and long-term resource planning decisions that must accommodate this growth. In the short to intermediate term, increased temperatures drive summertime demand for electricity, within the context of a built environmental system that buffers Southwest residents from climate extremes. An interruption in utility service would place a large percentage of the region at risk as interior climate control, water pumps, and other critical infrastructure would be unavailable, not to mention the potential for social disruption and economic loss attached to the outage, especially if an outage occurred during an extreme heat event, given potential for severe and immediate consequences.

The effect of increased temperatures on drought, water storage and supply, streamflow timing and runoff, and demand for these resources, is another aspect of increased average temperature that is of critical interest. Similarly, the relationship between heat and air quality is likely to be a persistent concern. The current regulatory framework is unlikely to affect utility operations in municipal areas like Phoenix, but were the regulatory framework to shift, this could be a future liability. Decision to build or invest in new generating resources has investment costs and revenue and portfolio benefits, but this decision also has long-term implications related to patterns of water availability (i.e. is the new location more vulnerable to water competition?); regulatory frameworks (i.e. what is the local pollution/regulatory context, and how does this decision connect to long-term carbon emissions portfolio decisions?); and infrastructure needs/risks (i.e. how are environmental risks managed in the new site vs the old site, what are the implications for change?).

Third, the risk assessment process highlights the importance of ***often unexpected (yet plausible) extreme events.*** While extreme events are generally rare and unpredictable, the scale of their impact can have outsized effects. Extreme events can also alter perception of climate risks, despite their relatively infrequent occurrence (i.e. high visibility high impact events last longer in memory than frequent or gradual low impact events or changes). Wildfire in the Southwest provides an example where specific events reveal underlying environmental risks and systemic infrastructural vulnerabilities. Wildfire exacerbated by drought and warming climate intersects with population growth and dependency on climate control, which can increase vulnerability within the electrical grid. This sets the stage for a disaster if a chain of events happens all at once. Climate risk management within a company or organization will likely not have the capacity to respond to extreme events, but risk management efforts that mitigate the risk of specific links in these chains of events could help reduce overall risk and exposure without attempting to address the risks in the entire system.

The 2011 Wallow fire in the White mountains of Arizona highlighted concerns about infrastructure vulnerability, given concerns about its potential to degrade or destroy regional transmission capacity, or the consequences of widespread power outages lasting for days or weeks following fire damage. As the Wallow fire burned, there was concern that it might threaten one of the two major transmission lines that feed into Tucson (McMahan, 2017). Contingency plans were thought to be enough to handle alternative transmission plans so that regional utility customers would not lose electrical service, and ultimately the fire did not cause a widespread outage. This event, however, did raise concerns about what might happen if fire events were to impact both major transmission lines into Tucson, and highlighted the value of ongoing and additional planning that incorporates these high-impact low-probability scenarios into ongoing climate risk management activities.

Cascading and interconnected risks are not isolated to a specific area of concern, but instead span across multiple risk areas. Threats are the result of linkages within the interconnected systems of water resource management, electrical service delivery, and energy portfolio management, and further complicated by demographic growth and climatic conditions in the Southwest. These cascading impacts are most visible during acute events that verge on disaster, where the consequences and aftermath are relatively easy to attribute directly, but interconnected effects also occur as a result of slow moving and long-term changes. In either case, a risk management framework that assesses the range of possible outcomes and identifies the data and information that could improve decision-making and planning with respect to these risks, is a key part of climate risk management for communities, critical infrastructure, and regional sustainability.

4. Discussion and conclusions

4.1. Climate risk assessment for business risk management

Sectoral approaches to climate risk management for business risk assessment have illustrated the potential value of integrating this perspective into how businesses make decisions (Demertzidis et al., 2015), including summaries of how electrical utilities manage climate risks (Weinhofer and Busch, 2013; Gerlak et al., 2018). The results presented here and in our technical report (Gerlak and McMahan, 2017) demonstrate elements of how a climate risk management application to business risk management works in practice for a regional electrical utility. First, this highlights a number of stand-alone climate risks that have bearing on planning and decision making for a utility. These are consistent with some of the concerns expressed by broader climate assessments (such as found in the NCA, IPCC, etc.), but our risk assessment demonstrates how these risks vary as they span across multiple timescales for a single utility grappling with the challenges of managing numerous climate risks and multiple data streams regarding these risks. The assessment process demonstrates how these risks can be narrowed in focus, and better understood in terms of their probability and severity, as well as opportunities for intervention or mitigation. Our process of engagement with TEP in a climate risk management process focused mainly on what has been described as a bottom-up approach (rather than top-down), and as emphasizing diagnosis rather than prescription regarding possible actions or interventions (Jones and Preston, 2011). The decision support element of this project brought to bear concerns about climate impacts and climate risk management that stemmed from a general understanding of the need to act on climate, and the iterative engagement with TEP helped us all better understand and characterize social and environmental phenomena could be applied to climate risk management focused on regional sustainability.

Second, the cascading impacts framework demonstrates how many of these climate impacts relate in a network of interconnected impacts, and this extends from extensive scholarship on the role of these cascading impacts in characterizing climate impacts and climate risks (Garfin et al., 2016; Moser and Hart, 2018; Lawrence et al., 2020). Planning and decision making that incorporates these connected and cascading impacts will find this complicates decision making and planning, but also forces a more holistic focus on climate risks. This includes a wider focus on the relationships between various elements of climate/environment and social factors, as well as the variable timescales of these variable elements, incorporating both synchronic and diachronic perspectives on climate risk management. This again refers to the bottom-up diagnostic perspective described in Jones and Preston (2011) and we see this orientation as one of the elements that led to our better shared understanding of climate risk management issues, developed in collaboration between our UArizona and TEP collaborators.

Finally, climate risk assessment within a business risk management framework highlights the role of a 'risks and opportunities' framing that may help encourage businesses to embrace climate risk management and decision making (Sussman and Freed, 2008). There is potential for a competitive advantage for those companies that are quick to embrace climate data, information, and decision support, especially if these data and information are seen as salient, credible, and legitimate by the end-user (Cash et al., 2003).

4.2. Collaboration and relationship management in climate services

Climate services development often focuses on identifying a gap within a stakeholder community and working to address that need by connecting-existing or conducting-novel research that would address those needs and gaps (Lemos et al., 2012). By approaching this as a collaborative research project *with* a stakeholder (Austin, 2004), and not simply providing services *for* a stakeholder, we attempted to break down the dichotomy between scientific expert and stakeholder/practitioner and part of the climate service we provided was the ongoing relationship with our TEP partners. This reflects the range and type of relationships seen in applied climate risk management research and climate services development (Meadow et al., 2015; Owen et al., 2019) – i.e. a continuum rather than dichotomy between researcher and practitioner. The co-production typology developed by Bremer and Meisch (2017: p. 13), further captures the messy complexity of co-production in this context. The collaboration between UArizona and TEP sits at the overlap of two categories they identified – 'iterative interaction' and 'extended science' which "promote consultative interaction between climate science providers and users" and "integrate non-scientists as co-investigators", respectively.

The UArizona/TEP collaboration supports the idea that co-production is not a singular concept, and highlights the evolution of collaborative projects as risk assessments turn to applied research, and applied research leads to eventual decision-making and planning. By focusing on both the expressed needs and concerns of the utility, and following up with a tailored approach (Cortekar et al., 2016) we focused on areas of known concern to provide data and information for these gaps and needs, as well as to explore areas of novel or emergent risk. The 'iterative interaction' and 'extended science' (Bremer and Meisch, 2017) helped UArizona researchers and TEP collaborators co-produce a qualitative risk assessment that will help inform TEP's integrated resource plan in future iterations, and provided an outlet for UArizona based climate and environmental expertise – another data point supporting collaborations between university and private sector partners.

This university-utility collaboration also demonstrates important aspects of applied research focused on climate risk management in collaboration with non-academic partners. First, it highlights the importance and value of relationship building, network development, and stakeholder engagement throughout the research process. This includes taking time to assess needs and motivations, and extends beyond a purely transactional or consultative relationship. The collaborative team needed time and space to 'breathe' – to explore TEP concerns, identify experts at UArizona, and work to identify, assess, and categorize the data and information about the risks we identified as part of a collaborative process. Second, this collaborative approach illustrates the need for space for collaborative engagements to grow and develop. There were flexible deadlines that allowed time to adapt and improvise based on an assessment of science and data needs, as well as motivations and perspectives on their eventual use in decision making and planning. Third, our TEP collaborators were well aware of climate risks and trends, as well as their implication for regional and sectoral impacts, but they wanted specifics – in some cases what novel and granular information meant for their decision making, and in other cases where the state of the science could not realistically add new. Finally, this collaborative engagement demonstrates that stakeholders and collaborators may have unexpected reactions to climate risks, and also see opportunities that recognize the reality of a changing climate, but adapt their practices to ensure a balance between short term plans and long-term sustainability.

This collaborative process also speaks to the promising facilitative role that universities can play in climate services and risk assessment management, which is a key element in helping to develop viable strategies for solving our sustainability challenges (Hart and Silka, 2020). Universities may take on many roles to support local climate change adaptation from conducting applied climate change research to assessing current risks to translating science for local decision makers and providing technical support and collaborative planning (Gruber et al., 2017). Based on our experience, good coordination between the university researchers, and clean lines of communication with the local partner are necessary. It may require locating a set of community interactions in a particular unit or research center at the university to help provide stability over time and allow for trust and interactions to be nurtured and developed. Ultimately, this will demand university leadership and buy-in, and perhaps linkages to the University Climate Change Coalition (UC3), of which UArizona is a member. As others have reported through their engagements in local climate change adaption, university involvement can help raise the legitimacy of the process (Gruber et al., 2017) and ultimately, help achieve greater sustainability (Trencher et al., 2014).

4.3. Limitations

Of course, we would be remiss if we did not acknowledge the challenges associated with this work. First, this project required time commitments on the part of UArizona researchers and TEP collaborators. There are limited funding mechanisms for applied interdisciplinary research that incorporates an open-ended assessment into the initial phases of the research, and this project depended on donations of time and effort as it evolved and developed. Given these funding limitations, this work was necessarily opportunistic based on the expressed concerns of TEP collaborators and the availability of UArizona researchers with relevant scientific expertise. This meant there were some areas where emergent science priorities were identified, but where the UArizona researchers lacked either the resources or the expertise to conduct the relevant analysis. In one case, this led to a follow-on project, wherein UArizona researchers working on wildfire risk mapping conducted additional research after the ABRI project was completed, focused on buffelgrass mapping updates and wildfire risk.

Second, the project was developed with replicability in mind, with the goal of expanding this process to work with other regional stakeholders who might have exposure related to climate risk. This was meant to connect university researchers who could provide tailored expertise and analysis of climate risk, with regional private sector partners, but there was no explicit roadmap for how this partnership was to develop. Thankfully, both parties were interested in exploring this relationship as a pilot process that demonstrated the viability of this approach. This flexible and iterative approach also facilitated the participation of graduate students, who were able to make substantive analytical contributions and learn more about the process of collaborative research and climate services co-production working alongside their faculty mentors, and for TEP this was an opportunity to work with university graduate students and faculty. This shared understanding between UArizona and TEP collaborators mitigated expectations about timing, deliverables, and even how the project was coordinated, but this would certainly be different under the heading of a professional consultancy.

Finally, the end product was primarily qualitative, given the broad scope of the initial risk assessment, and the challenge of connecting social and environmental phenomena to specific economic costs or opportunities, especially within the context of energy systems economics and vulnerability at a regional scale. The opportunistic nature of the research also meant there were important areas left unexplored, owing to lack of time, resources, or expertise, and other areas where only a passing assessment was feasible. In particular, research that connects the economic impacts of specific strategic resource planning decisions, as well as the downstream social impacts of these scenarios, would be of great use to utilities and of great interest to university researchers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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