An Interdisciplinary Approach to Assessing Vulnerability of US Midwest to Drought and Heat Waves

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ABSTRACT

More severe summer heat waves and droughts in the US Midwest attributable to climate change as well as changes in population distribution can create significant operational stress in the future. Planning options could potentially reduce these vulnerabilities. Costs and benefits of these options must account for population shifts and the impact of climate on electricity service areas, ranges of electricity demand and supply limitations, modification of demand in response to new end-use technology and linking water usage with power plant outages. Three adaptation scenarios based on changes in electricity supply and demand for the greater Chicago, Illinois area were explored by applying a unique set of coupled infrastructure models created by US National Laboratories. The authors find that due to projected population changes in the region, the total number of metered customers approximately doubles by 2054 and total electric energy usage increases over 70%. The latter effect is due in part to projected increases in maximum summer temperatures and frequency of heat waves in the region. Concomitantly, low availability of water during drought conditions and high temperature effluent discharges during heat waves and higher overall temperatures will threaten operations for 30% or more of current power plant capacity reducing critical supply during peak demand. These conditions could lead to a severe supply reserve deficit by 2054 and rapidly declining capacity margins during prior decades. New technology and other changes such as effective demand-based rates could substantially modify customer usage post-2024. Additionally, many water-cooled power plants near the end of their operational lives could be replaced by more water efficient generation, at least partially mitigating these effects.

Keywords: climate change, energy, water, heat waves, drought

INTRODUCTION

More than 60% of the country experienced drought during the summer of 2012 [1], including the US Midwest. Other notable Midwest droughts have occurred in 2005 and in 1987-88 [2]. As a result, the region has seen power plant shutdowns due to high ambient temperatures and utilities have frequently had to request exemptions from mixing zone temperature limits in order to maintain generation [1]. The National Climate Assessment [3] projects that events like these combined with extreme heat will become more frequent, longer, and more intense in the U.S Midwest and in other regions in coming decades. These climate events will also impact stream flows and stream temperatures further threatening power plant operations. Growing demand for electricity, projected to increase by 0.5% per year in the residential sector and by 0.8% in the commercial sector from 2013 to 2040 [4], will further intensify effects. One preliminary analysis [5] suggests that, under such conditions, as much as 30 percent of the thermal electricity generation capacity of the nine-state midwest region might be at serious risk of de-rating. We examined the adaptive capacity of the United States Midwest electricity infrastructure to the combined effects of increased drought and heat waves in the region under a business-as-usual climate change projection because an extended heat wave and drought condition in the Midwest region for the 2050s would reveal major exposures of both energy and water infrastructures.

METHODOLOGY

To determine Midwest electricity infrastructure response to mid-century drought and heat waves, we employed a suite of three tools: i) the Connected Infrastructure Dynamics Model [6], for determining population allocation and climate variables to electricity service areas; ii) the Technology Insertion and development Profiles (TIP) tools [7], to establish ranges of electricity demand and supply limitations and their modification in response to technological advances; and iii) the Soil and Water Assessment Tool (SWAT) [8], to assess climate driven changes in water supply for thermoelectric generation. We used other semi-empirical methods to link water variables with power plant outages. The Midwest region was chosen because of its vulnerability both to droughts and to heat waves, and because a combination of both extreme events together in the region could have implications not only for the region itself, but also for the greater region it serves. We constructed this extreme events scenario based on a combined event determined by worst drought conditions and worst heat wave under historical (e.g., 1988-89 drought and 1995 heat wave) and RCP 8.5 projections [9].

We analyze three utility adaptation scenarios based on assumed changes in supply and demand for the greater Chicago, Illinois area (see box below) as defined in the planning exercises of the Eastern Interconnection Planning Collaborative (EIPC). They represent a wide range of growth in base energy demand and changes in supply and policy standards--specifically, a national renewable portfolio standard and carbon emission standards [10].

Scenario 1 (EIPC F1S17), no new policies or regulations on carbon are implemented, no renewable portfolio standard (RPS) or new EPA regulations are enacted. Roughly half of the coal and nuclear fleet are retired and replaced with combined cycle generation, and to a lesser extent, wind farms.

Scenario 2 (EIPC F6S10) supposes a regionally implemented 30% national RPS resulting in a similar retirements of coal and nuclear generation, which is replaced largely with wind farms.

Scenario 3 (EIPC F6S10 and F8S7 adds a national carbon constraint with 42% reduction in 2030 and 80% by 2050, 30% national RPS, increased energy efficiency, Demand Response (DRP), Distributed Generation (DG) and other initiatives. Retirement of all coal and oil plus some nuclear capacity replaced largely with wind farms and natural gas combined cycle.

We compare a "no adaptation" scenario to the three EIPC scenarios to assess adaptation "payoffs", based on projected changes in population; increases in maximum summer temperatures and frequency of heat waves; total electricity use; electricity supply deficit*;* and time series of supply margins. Finally, we examine ways in which technological and policy changes, along with changes in electricity generation can modify these outcomes to meet excess electricity demand in coming decades, potentials of selected adaptation strategies for balancing supply and demand under extreme conditions, and implications of possible technological change.

RESULTS

First considered is the ability of the existing water and electricity infrastructure to meet future projected growth in electricity demand resulting from the combined effects of changes in population, temperature, drought and heat wave. For this "no adaptation" scenario, the projected number of metered customers approximately doubles in 50 years, i.e., 3.1 to 6.4 million from 2004 to 2054, and total electricity use increases 72% to 237,272 Giga-Watt hours GWh per year by 2054. These changes are driven in part by temperature increases (up to 2.8 degree F increase in July mean temperature) and this increase, along with economic growth and population changes, drive demand growth [11].

In nearly all years, system reserve margins [12] fall below industry standard levels. Figure 1 indicates projected margin values are well below NERC's lower bound or 5% by 2034 with no adaptation, the system is becoming unsustainable [11, 12, 13]. Margins estimated for years 2044 and 2054 indicate that the system is clearly not viable (demand greatly exceeds supply) under the extreme conditions postulated. Demand side reductions prior to 2015 were modeled in this case; however, they represent less than 6% of end-point technology insertion potentially viable by 2054.A similar analysis was conducted for the EIPC Scenarios 1-3, as well as for the wider Midwest region. Extension of this base case outward indicates an electricity supply shortfall for two of the four sub regions examined and surplus supply in the other two. These results indicate that operational stress could be greatly exacerbated by a heat wave that occurs over short time intervals, but the effects would likely occur in some areas but not others. An example of this outcome was reported for the 2007 Southeast drought, which caused reductions in capacity in two large Duke Energy fossil-fuel power plants due to warmer source water, which led to short-term regional blackouts in the Carolinas [14]. The extrapolation of effects reported in the Chicago subarea becomes about an order of magnitude greater regionally assuming Chicago is representative of demand and supply mix across the region.

Water scarcity in the no adaptation case amounts to an approximate 27% reduction in generating capacity for future years in Illinois and 30% reduction in the Chicago area window by 2050. Specifically, the state of Illinois could operationally lose 13,800 Mega-watts (MW) of capacity.

Can New Technology Mitigate These Risks?

Significant increases in electricity demand through 2054 due to increases in heat wave frequency and duration will require more resilient types of electricity generation along with increased end-use efficiency. Many adaptation options are available. These options include combinations of technology insertion at the demand side and retrofit or replacement of generation plants at the supply side. The assumed types of technology insertion include a variety of policy and end-use measures that result in substantial demand reductions:

- Solar photovoltaic generation
- Demand side management and smart metering
- Demand response programs
- Plug-in electric vehicles

In the aggregate, these options can be targeted to reduce electricity consumption even under extreme conditions such as heat waves. In fact, new technology could potentially offset all temperature-induced demand in Scenarios 2 and 3, including heat wave effects. In order for this outcome to occur consistently, it would require agile rate signals to be communicated via smart metering or other means to provide a routine trade-off in consumer behavior and appliance stock.

Figure 1. Greater Chicago Electricity Generating Capacity Margin, 2015-2054

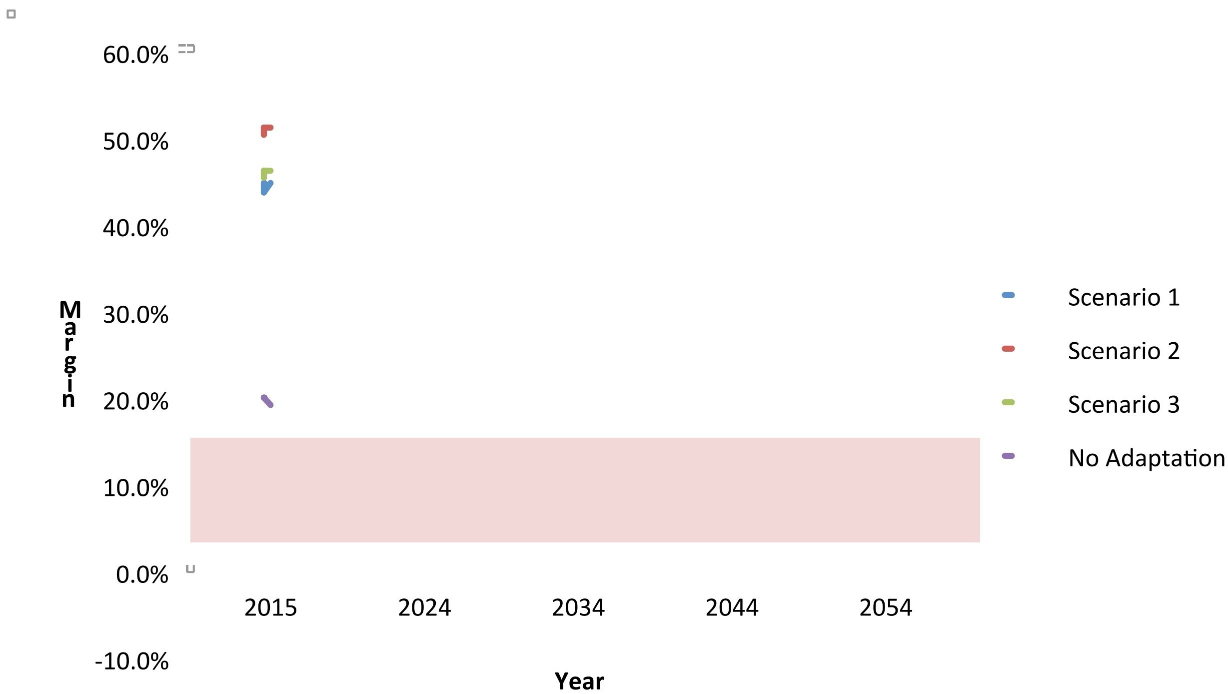
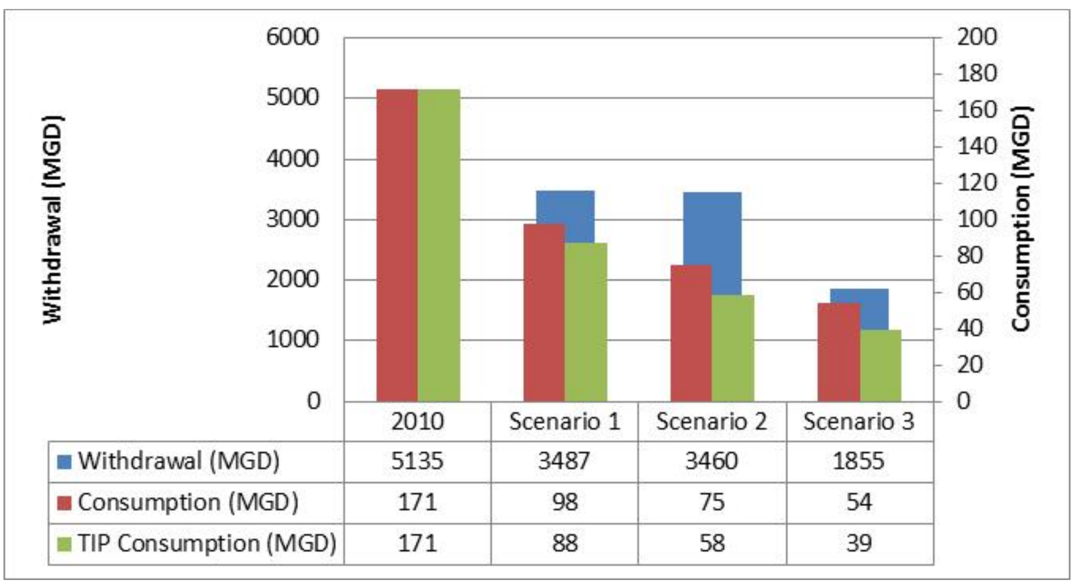


Figure 2. Thermoelectric power plant withdrawal and consumption Scenario 1-3



In order to meet demand required during heat wave conditions, planning for increased electricity consumption will also mean planning for increased transmission lines for import and export of power. Decadal periods for which capacity margins are low will require additional power to be imported from other sub regions, along with additional transmission capacity for this purpose. Transmission usually does not displace thermal generation economically for extended periods due to line congestion and volatile market pricing. Therefore, an effective planning strategy will require both new generation and transmission capacity to be incorporated.

As plotted in Figure 1, the steep rise in capacity margin pre-2044 is not a typical trajectory. This rise may reflect an uneconomic addition of capacity (as currently reported by EIPC). As decades progress, excess capacity will be trimmed in the forecast to lower system margins. An important scenario-specific factor is the degree to which new technology results in lower net demand for a variety of customer groups. Drivers that cause these differences are mainly utility rates trends over the study period. Scenario 3 assumes a "high" rate trend while Scenario 1 assumes "low" rate trend. The latter is based on EIA's current national projection; the former doubles those rates by 2054. This driver results in lower clearing prices for technology insertion and greater demand reductions or shifting of demand patterns due to greater economic incentives. Historic pricing data indicate up to 6:1 increases in electricity rates could occur for short periods during extended heat waves, while average rates show lower increases [15].

Water Implications for All Scenarios

Figure 2 plots results for water withdrawal and consumption for thermoelectric power generation**.** Here, significant declines in withdrawals and consumption for all scenarios largely reflect retirements of coal and nuclear generation and the replacement with low water use natural gas combined cycle and wind. Significant declines in withdrawals and consumption as indicated by red, blue bars reflect retirements of coal and nuclear generation and replacement with low water use methods. Green bars indicate water consumption generally declines with added technology Insertion.

As shown by this study, water limitations due to drought conditions and elevated temperatures could limit energy production. Plants particularly at risk to these conditions are largely coal and nuclear plants using open loop cooling. Notably thermoelectric power production withdraws more water than any other sector in this region, and many of these plants have experienced water related issues during past droughts. Thus, adaptation scenarios that incorporate retirements of coal and nuclear generation replaced with low water use generation methods such as natural gas combined cycle, solar and wind generation will be important mitigation options. Some types of plant retrofit will also reduce water withdrawal and consumption, but not without operation and maintenance costs and reductions in plant productivity. Generation at risk of climate related water issues is reduced to less than 10% of operating capacity under these scenarios; and much less water is projected to be used in a future in which the most vulnerable plants are being retired and replaced with drought resilient closed loop systems.

CONCLUSIONS

Intensifying climate conditions threaten our nation's built infrastructure. To explore this concern for coupled energy and water infrastructure, a suite of analytical tools were assembled to address climate, population demographics, electricity demand, changes to electricity supply in response to technological advances, water demand and water impacts on thermoelectric generation. Within the case study examined, electricity demands were projected to increase by 72% while extreme drought and heat wave could add another 14% to the load. In response to changing environmental and economic conditions, population shifts from rural to urban were likewise noted. Thirty percent of the existing thermoelectric generation capacity was identified as vulnerable to increased cooling water temperatures and/or supply limitations posed by intensifying drought and heat waves. Several alternative futures borrowed from the Eastern Interconnection Planning Collaborative were explored assuming different future generation portfolios reflecting different future policy pathways (now considering climate change). In cases favoring high renewables penetration, supply margins did not achieve industry standards. However, the TIP modeling helped set these results in a better context, projecting double digit improvements in supply margins realized through market driven technology insertion. Although generation capacities expanded in all three scenarios, water withdrawals and consumption decreased reflecting retiring coal and nuclear generation, which are replaced with low water use renewables and natural gas combined cycle. Expected retirements were also seen to reduce the generation capacity at risk to extreme drought and heat wave to less than 10% of the fleet.

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NOTES AND REFERENCES

1. Zamuda C, Mignone B, Bilello D, Hallett KC, Lee C, Macknick J, Newmark R and Steinberg D 2013 *The U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather* US Department of Energy Report DOE/PI-0013.
2. Illinois State Water Survey, http://www.isws.illinois.edu/hilites/drought/
3. NCA US Global Change Research Program (USGCRP) 2014 Climate Change Impacts in the United States: The Third National Climate Assessment WashingtonDC U.S. Global Change Research Program.
4. EIA Annual Energy Outlook 2015 http://www.eia.gov/forecasts/aeo/section_deliveredenergy.cfm
5. Cook MA, King CW, Davidson TF and Webber ME 2015 Assessing the impacts of droughts and heat waves at thermoelectric power plants in the United States using integrated regression, thermodynamic, and climate models *Energy Reports* **1** 193-203.
6. Wilbanks, T.J., S.J. Fernandez, and M.R. Allen (2015). Extreme Weather Events and Interconnected Infrastructures: Toward More Comprehensive Climate Change Planning, *Environment Science and Policy for Sustainable Development*, **57/4**.
7. Cohn J, Toole GL and Dreicer J 2014 Analysis of Climatic Impacts to Connected Infrastructure Dynamics: Technology Insertion Profile (TIP) DOE Climate Modeling PI Meeting (poster) May 12-15Potomac MD.
8. Neitsch SL, Arnold JG, KiniryJR and Williams JR 2011 *Soil and Water Assessment Tool Theoretical Documentation Version 2009* Texas Water Resources Institute Technical Report 406 Texas A&M University System College Station TX .
9. Gao Y, Fu JS, Drake JB, Liu Y and Lamarque J-F 2012 Projected changes of extreme weather events in the eastern United States based on a high resolution climate modeling system *Environ. Res. Lett.* **7/4** 044025.
10. http://www.eipconline.com/.
11. This refers to reductions in demand attributable to new technology additions in each year. This offset

yields cumulative MWh over the study period but it is stated here as a yearly impact for the specific years reported. The numbers shown can be considered a [1]mid-decadal snapshot of what is happening in the demand layer.

12. NERC's 2016 Summer Reliability Assessment indicates that the reference margin level varies by 12 to 20% with only 1 of 20 areas reporting a reference margin of 20%. The median margin is approximately 15% but values as low as 6% have been previously reported.
13. "Margin nameplate" equals percent "Margin demand" exceeds capacity minus retirements, cooling penalties and new technology impacts.
14. Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers, and S. Tellinghuisen. 2011. Freshwater use by U.S. power plants: Electricity's thirst for a precious resource. A report of the Energy and Water in a Warming World initiative. Cambridge, MA: Union of Concerned Scientists. November.
15. US Energy Information Administration data provided by PJM, ISO-NE and NYISO

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