Drought impacts on the electricity system, emissions, and air quality in the western US

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Section 1: Overview

Climate change can influence energy systems by altering energy supply, demand, and transmission, leading to significant economic and environmental impacts. For instance, existing work highlights how a changing climate will affect electricity demand and energy expenditure (1, 2), how it can influence how much of a given energy source (e.g. hydropower) can be utilized (3), and how it can influence the operations of thermal power plants (4).

Yet the overall societal costs of climate-related disruptions to the energy system could extend beyond the channels explored in existing work. In particular, climate disruptions could result in increases in electricity generation from fossil fuel sources, if marginal electricity generation source used to cover short-run increases in demand or decreases in supply remains reliant on fossil fuels. Increased fossil generation could then result in increased greenhouse gas (GHG) and air pollutant emissions, with emissions increases perhaps occurring far from the location of the climate shock, given the spatially interconnected nature of many energy systems. The associated economic and health impacts of these climate-induced emissions are often unaccounted for in existing analyses.

Section 2: Research approach

In this paper, we study the impacts of drought on the electricity system and the consequent effects on GHG emissions, air quality, and human health in the western United States (US). We use empirical data on plant-level generation and emissions from individual fossil fuel power plants, runoff (i.e. the amount of water available on surface and below the surface), and observational air quality measured by surface monitors from 2001-2021. Our analysis accounts for the trans-boundary impacts of drought on fossil fuel generation and pollutant emissions, due to the import/export of electricity across three electricity regions. We first develop a statistical model between plant-level electricity generation and runoff anomalies in each of the three electricity regions. For each plant, we then calculate the drought-induced generation, defined as the changes in generation as a result of the runoff anomalies (relative to the 1980-2021 average).

To estimate the impacts on air quality and related health damages, we quantify whether predicted drought-induced emissions of SO_2 and NO_x affect surface $PM_{2.5}$ concentration measured at nearby air pollution monitors. We then calculate the monetized damages from excess mortality due to observed $PM_{2.5}$ changes using an empirically derived concentration response function that relates short-term changes in air pollution to mortality and a value of statistical life of $10.95 million recommended by the US EPA. We further quantify the monetized damages of drought-induced GHG emissions by accounting for increased CO_2 emissions using the social cost of carbon ($117 per ton), and methane (CH_4) leakage using the social cost of methane ($1257 per ton) and a 2.3% leakage rate across the life cycle of the gas production and usage.

Finally, to assess impacts under future climate and energy production scenarios, we combine our empirical estimates of plant-level emission changes with climate projections and stylized electricity sector scenarios. We use the average 2030-2059 projected runoffs from The Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model ensemble. We consider three potential scenarios in the electricity sectors using results from existing energy system model projections: replacing coal power plants with natural gas plants, increased penetration of carbon capture and storage (CCS), and increased penetration of renewable energy and battery technology.

Section 3: Research results

Our research finds that drought increases electricity generation from fossil fuel plants. Compared to the average conditions in 1980-2021, the electricity generation from the fossil fuel plants on average increased by 35%, 11%, and 9.5%, in California (CA), Northwest (NW), and Southwest (SW) in the driest month during the study period.

Over 54% of this drought-induced generation is trans-boundary, with drought in one electricity region leading to net-imports of electricity and thus increased pollutant emissions in other regions. For example for NW, when comparing a dry period relative to a wet period, we find a 23% increase of net export of electricity from CA to NW, and a 7.2% increase of net export from the SW to NW. Magnitudes of the import/export changes are consistent with the trans-boundary effects of drought-fossil generation quantified above. These results suggest that when hydropower production is reduced in the NW under drought, less power is available for export to either CA or SW and therefore fossil fuel plants in CA or SW would need to increase their electricity generation to fill this gap.

We find that the drought-induced emissions account for ~12% of the total regional CO_2 emissions from the electricity sector, ~6% of the total NO_x emissions, and ~8% of the SO_2 emissions during extreme drought periods (e.g., spring and summer during 2001). Drought-induced emissions of SO_2 and NO_x from fossil fuel plants increases the surface $PM_{2.5}$ near the power plants (in particular, within a 50km radius). We also find evidence that suggests increases in surface $PM_{2.5}$ are more likely to be associated with drought-induced emissions from plants at the upwind location of the monitor, further strengthening our causal claims.

As most of the recent 20 year period is drier than the 1980-2021 long-term average, we calculate that the western US has experienced a total net damage of $20 billion during this period. Drought-induced CO_2 emissions account for $14 billion, or 70% of the total damage. $PM_{2.5}$-associated mortality accounts for $5.1 billion (25% of the total damage), and CH_4 leakage accounts for $0.9 billion (5% of the total damage). These monetized damages exceed direct economic impacts reported by previous studies by 1-2 folds, which estimated direct economic cost due to the reduction in hydropower and the drought-induced increase of electricity demand (5).

As most climate models project increasing drought risks over the western US, damages associated with drought-induced emissions remain substantial. These drought-induced economic and health damages, however, could be substantially lower under scenarios with lower GHG emissions, by as much as 73% lower.

Surprisingly, the projected transitions in the electricity sector have modest effects in mitigating the damages from drought-induced fossil generation. Increased penetration of renewable energy and energy storage only reduces the damages by 5.4% in 2050. These modest effects are in sharp contrast with the total emission mitigations that could be achieved under the same strategy. Total CO_2 emissions from fossil fuel plants would decline by 72% under the same scenarios. These disparities are due to the differences between the projected changes in marginal energy sources (i.e. those sources used to cover short-run increases in demand or decreases in supply) and overall energy sources (i.e. those sources used to meet overall average demand) in the future.

Section 4: Conclusions

In conclusion, we empirically quantify the impacts of drought on fossil fuel power plants in the western US and the consequent effects on emissions and air quality. Damages through these channels are estimated to be 1.2-2.5x the increase in direct economic cost of drought-induced fossil fuel electricity generation. Under future climate, these drought-induced impacts likely remain large due to increasing drought risks, and we find that even rapid expansion of renewable energy has limited ability to curb these impacts. In other words, the electricity sector will become harder to be “fully decarbonized” if we account for the increasingly frequent drought shocks and the associated GHG emissions in energy systems with at least some hydro.

Our method and findings are globally relevant as many countries that heavily rely on hydropower have experienced increasing drought risk due to climate change. Globally, we identify 19 countries that are vulnerable to drought-induced shocks to their electricity and energy system, primarily located in Central and South America, Africa, and South East Asia.

References

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