



Assessing Climate-Induced Risks to Critical Energy Infrastructure: A Comparative Analysis of Hydropower and Oil and Gas Systems in Drought-Prone U.S. Regions

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Abstract

Climate change poses escalating threats to energy infrastructure in the western United States, yet the interdependencies between affected sectors remain insufficiently characterized. This study develops a comparative, empirically informed framework for understanding how drought transfers vulnerability across hydropower and oil and gas systems. Drawing on the IPCC vulnerability assessment approach, cascading-risk perspectives, and socio-technical systems theory, the study advances four hypotheses regarding mechanisms of drought-induced cross-sector vulnerability transfer. Through a structured comparative synthesis of generation data, reservoir levels, water consumption records, and emissions inventories across the western United States (2001-2024), the analysis documents that hydropower facilities have experienced cumulative generation declines of up to 23% since 1980 (Turner et al., 2024), with individual drought years producing output reductions of 48-81% at major facilities. Simultaneously, hydraulic fracturing water use per well has increased up to 770% (Kondash et al., 2018), predominantly in high water-stress regions. The assembled evidence is consistent with a cascading dynamic in which hydropower shortfalls necessitate fossil fuel substitution, which amplifies water demand and emissions, potentially reinforcing drought conditions. Published estimates attribute approximately \$20 billion in monetized damages to this mechanism over 2001-2021 (Qiu et al., 2023). The analysis further suggests that threshold effects in reservoir levels may intensify cross-sector stress nonlinearly. The study proposes integrated adaptation pathways bridging water, energy, and climate governance, and identifies priorities for future empirical and modeling research.

Keywords: climate change, energy infrastructure, hydropower, drought, water-energy nexus, cascading risk

1. Introduction

The United States energy sector faces growing challenges from climate change, with increasing temperatures, shifting precipitation patterns, and more frequent extreme weather events threatening the reliability and resilience of critical infrastructure (Cronin et al., 2018; DOE, 2013; Zamuda et al., 2018). The western United States, home to approximately 45% of U.S. hydropower capacity and significant oil and gas production, is particularly vulnerable to drought conditions that have intensified dramatically in recent decades. The period from 2000 to 2021 represents the driest 22-year interval in the southwestern North American record spanning at least 1,200 years, with approximately 42% of this drought severity attributable to anthropogenic climate change (Williams et al., 2022a). This megadrought has exposed critical vulnerabilities across the energy

sector, from the near-shutdown of major hydroelectric facilities to escalating water competition for oil and gas operations.

Substantial literature exists examining climate risks to individual energy sectors, including hydropower vulnerability assessments (Turner et al., 2024; Udall & Overpeck, 2017), oil and gas water footprint analyses (Kondash et al., 2018; Scanlon et al., 2022), and cross-sector energy system modeling (Bartos & Chester, 2015; Yalew et al., 2020). However, a significant gap persists in the comparative analysis of how drought simultaneously affects both hydropower and oil and gas infrastructure within the same geographic regions. Existing studies tend to treat these sectors in isolation, largely overlooking the cascading interdependencies that may amplify systemic risk. More fundamentally, the prevailing approach describes the consequences of drought for individual sectors but does not explain the mechanisms through which vulnerability transfers across sectors and intensifies under specific conditions.

This study addresses that gap by developing drought not merely as a parallel hazard affecting two sectors independently, but as a system-level stressor that triggers cross-sector vulnerability transfer. The core argument is as follows: when drought reduces hydropower generation, grid operators increase reliance on natural gas-fired generation to maintain supply reliability. This substitution increases both greenhouse gas emissions and water consumption for thermoelectric cooling, intensifying competition for scarce water resources simultaneously needed for hydraulic fracturing and enhanced oil recovery. The resulting emissions increase contributes to the warming that drives drought intensification, creating what may constitute a self-reinforcing cycle. This mechanism, termed here *drought-mediated infrastructure risk transfer*, operates most acutely under conditions of high hydropower dependence, available fossil backup capacity, and fragmented water governance.

The study advances four hypotheses regarding the conditions under which this transfer mechanism operates, its nonlinear dynamics, and its governance dimensions. Empirically, the analysis draws on generation data, reservoir records, water consumption inventories, and emissions datasets spanning the western United States from 2001 to 2024. Theoretically, it combines the IPCC exposure-sensitivity-adaptive capacity framework with cascading-risk perspectives drawn from complex adaptive systems and socio-technical infrastructure theory. The study is designed as a structured comparative synthesis: rather than pursuing causal identification through econometric estimation, it assembles a cross-sector evidence base from published data and interprets it through an integrative theoretical lens. The contribution is twofold: a comparative vulnerability assessment grounded in the best available empirical evidence, and a conceptual framework for understanding drought as a mechanism of cross-sector risk amplification rather than a collection of parallel sectoral impacts.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and develops the theoretical framework and hypotheses. Section 3 describes data sources and analytical strategy. Section 4 presents results organized around the four hypotheses. Section 5 discusses implications for governance and adaptation. Section 6 concludes.

2. Literature Review and Theoretical Framework

Climate risks to hydropower

Hydropower provides approximately 6-7% of total U.S. electricity generation and over 60% in the Pacific Northwest (DOE, 2013), making it among the most climate-sensitive energy sources in the national portfolio. Turner et al. (2024) conducted a comprehensive analysis of 610 U.S. hydropower plants and found that annual capacity factors have declined at four-fifths of facilities since 1980, with a median decline of 2.6 percentage points per decade. The cumulative generation decrease amounts to 23% before accounting for capacity

upgrades, described by the authors as “akin to retiring a Hoover Dam once every two to three years.” Notably, changes in water availability explain energy decline in only 21% of plants, with equipment deterioration and operational changes for non-power objectives contributing to the remainder, suggesting that drought is a necessary but not sufficient condition for the observed decline pattern.

The Colorado River system exemplifies how drought transforms from a temporary perturbation into a structural condition. Udall and Overpeck (2017) documented a 19% decline in Colorado River flows during 2000-2014 relative to the century-long average, with approximately one-third attributable to temperature increases of 0.9°C. Their projections indicate flow reductions of 20% by mid-century and 35% by end-century under business-as-usual emissions. Williams et al. (2022a) subsequently confirmed that the ongoing megadrought represents a regime shift rather than a cyclical anomaly. This distinction matters analytically: if the twentieth-century hydrological baseline was itself anomalously wet, as paleoclimate data suggest (Woodhouse et al., 2010), then infrastructure designed and operated against that baseline carries a structural vulnerability that drought merely reveals.

The economic consequences extend well beyond lost generation revenue. Szinai et al. (2024) coupled water and electricity system models across the Western Interconnection and found that climate change could decrease total hydropower generation by up to 23% (56 TWh), requiring 24-139 GW of additional generating capacity at costs up to \$150 billion over 2030-2050. Voisin et al. (2020) demonstrated that Northwest hydropower generation explains approximately 40-50% of generation variability in the Southwest, Rockies, and Southern California, illustrating how drought impacts propagate through the interconnected grid far beyond the affected watershed.

Climate risks to oil and gas infrastructure

The oil and gas sector faces a distinct but overlapping set of climate-induced vulnerabilities centered on water scarcity, wildfire exposure, ground subsidence, and coastal flooding (Cruz & Krausmann, 2013; DOE, 2013). Water scarcity represents the most direct drought-related risk. Kondash and Vengosh (2015) first quantified the water footprint of hydraulic fracturing across major U.S. shale plays, and Kondash et al. (2018) subsequently documented per-well water use increases of up to 770% in the Permian Basin between 2011 and 2016 (from 4,900 to 42,500 m³ per well), with water-use intensity rising ubiquitously across all U.S. shale basins. Scanlon et al. (2017, 2022) found that water demand for hydraulic fracturing peaked at approximately 35% of non-mining water consumption in the Permian Basin in 2019, with approximately 1,100 wells drilled into the Ogallala Aquifer for water sourcing in that year alone. The Ceres report established that 57% of hydraulically fractured wells are located in areas of high or extremely high water stress (Freyman, 2014), creating a structural dependence on water resources that are simultaneously threatened by the climate conditions the industry’s products help to produce.

Wildfire represents an increasingly significant threat to oil and gas surface infrastructure. Westerling (2016) demonstrated that western U.S. wildfire activity has increased sharply due to earlier spring snowmelt and longer dry seasons, and Gonzalez et al. (2024) documented 102,882 wells in wildfire burn areas between 1984 and 2019, with a five-fold increase in affected wells per year and projections of approximately 205,670 wells in high wildfire risk areas by late century. Ground subsidence driven by drought-induced groundwater overdraft threatens buried pipeline infrastructure: California’s Central Valley has experienced up to 28 feet of cumulative subsidence, with oil field infrastructure in Kern County situated within this zone. Coastal infrastructure faces additional hazards from sea-level rise and hurricane intensification (Sichani et al., 2020; Zamuda et al., 2018), though these risks operate through mechanisms distinct from the drought-mediated pathway that is the focus of this study.

Cross-sector interdependence and the substitution effect

The critical gap in existing literature lies in the treatment of hydropower and oil and gas vulnerabilities as parallel rather than interconnected. The DOE (2013) identified that "vulnerabilities of interdependent sectors may compound one another and lead to cascading impacts," but subsequent research has largely failed to operationalize this insight. Van Vliet et al. (2016) analyzed over 25,000 power plants globally but examined hydropower and thermoelectric plants as separate populations. Yalew et al. (2020) provided a meta-analysis establishing that hydropower faces the widest range of climate impacts (-40% to +20%), while the IPCC AR6 (2022) concluded with high confidence that solar and wind are comparatively less vulnerable, but neither study examined how vulnerability in one sector reshapes the risk profile of another.

Qiu et al. (2023) provided the most comprehensive empirical analysis of the substitution mechanism to date, analyzing 681 fossil fuel units across the western U.S. over 2001-2021. Under extreme drought, individual fossil fuel plant generation increases up to 65%, with over 54% of drought-induced generation occurring as transboundary effects. Total monetized damages reached \$20 billion, with CO₂ emissions accounting for 70% and PM2.5-related mortality 25%. By 2050, drought-induced emissions could comprise up to 41% of California's electricity emissions during extreme drought years. Critically, even rapid renewable expansion reduces these damages by only 5.4%, because renewables cannot fully substitute for lost hydropower's dispatchable characteristics without massive storage (Szinai et al., 2024). This finding underscores that the substitution problem is not merely an artifact of the current generation mix but a structural feature of the water-energy system.

Theoretical framework and hypotheses

This study positions drought as a system-level stressor that triggers cross-sector vulnerability transfer under specific structural conditions. The analytical framework combines three theoretical perspectives. First, the IPCC exposure-sensitivity-adaptive capacity model provides the organizing structure for sector-specific vulnerability assessment. Second, cascading-risk theory from complex adaptive systems literature, particularly the resilience framework pioneered by Holling (1973) and elaborated by Folke et al. (2004), explains how perturbation in one infrastructure domain propagates to others through interdependence, feedback, and threshold effects. Third, insights from socio-technical systems and water governance scholarship illuminate how institutional arrangements mediate the distribution of climate risk across sectors and communities. Together, these perspectives yield a framework in which drought is understood not as an exogenous shock to independent systems, but as an endogenous stressor whose effects are amplified by the very interdependencies that characterize modern energy infrastructure.

From this framework, the study advances four hypotheses that organize the comparative analysis and guide the interpretation of cross-sector evidence:

Hypothesis 1. Prolonged drought is associated with substantial reductions in hydropower output in the western United States, with the magnitude of decline varying by basin hydrology and reservoir storage capacity.

Hypothesis 2. Hydropower shortfalls correspond to increased fossil-fuel electricity generation, particularly natural gas, producing a substitution effect with associated emissions and water consumption implications.

Hypothesis 3. Regions characterized by higher water stress and stronger hydropower dependence exhibit more pronounced cross-sector vulnerability under drought conditions, suggesting that vulnerability transfer is structurally conditioned rather than spatially uniform.

Hypothesis 4. Threshold effects in reservoir levels intensify substitution dynamics nonlinearly: beyond critical reservoir elevations, cross-sector stress may accelerate rather than progress incrementally.

These hypotheses are assessed through structured comparative analysis rather than formal statistical testing. For each hypothesis, the study assembles the relevant evidence from published datasets and existing studies, evaluates whether the observed patterns are consistent with the proposed mechanism, and identifies the conditions and qualifications under which the evidence is most and least supportive. This approach yields directional assessments of plausibility and scope rather than point estimates or causal claims.

3. Data and Methods

Geographic scope and data sources

The study focuses on the western United States, encompassing four sub-regions selected for their combined significance to both hydropower and oil and gas operations under drought: the Colorado River Basin (Arizona, Colorado, Nevada, Utah, Wyoming), hosting Hoover Dam and Glen Canyon Dam; California, with major hydropower facilities and Kern County oil fields producing approximately 70% of state output; the Pacific Northwest (Washington, Oregon), dominated by the Columbia River hydropower system; and the Permian Basin (Texas, New Mexico), the largest U.S. oil-producing region accounting for approximately 40% of domestic crude under conditions of extreme water stress.

The analysis draws on multiple publicly available datasets. Hydropower generation data come from the EIA Electricity Data Browser (monthly and annual generation by plant, 2001-2024). Reservoir elevation and storage data come from the Bureau of Reclamation's water database (daily records, 2000-2024). Drought conditions are characterized using the U.S. Drought Monitor and Palmer Drought Severity Index. Oil and gas water consumption data derive from FracFocus and state regulatory agencies (2011-2023). Well location data come from Enverus and state commissions. Wildfire perimeters come from MTBS and NIFC databases (1984-2024). Emissions data come from EPA Air Markets Program, and pipeline incidents from PHMSA (2010-2024).

Analytical strategy

The analytical approach is a structured comparative synthesis. The study does not employ formal econometric estimation or causal identification methods; instead, it assembles the most complete available data series for each hypothesis and evaluates the evidence through descriptive comparison, trend documentation, and cross-regional pattern analysis. For Hypothesis 1, hydropower generation trends are examined at the plant and regional level alongside drought severity indices, drawing primarily on EIA generation data and Bureau of Reclamation reservoir records. For Hypothesis 2, the temporal correspondence between hydropower shortfalls and fossil fuel generation increases is documented across balancing authorities, drawing on published substitution estimates, particularly Qiu et al. (2023). For Hypothesis 3, sub-regions with contrasting structural characteristics (hydropower dependence, oil and gas water demand, governance arrangements) are compared to assess whether vulnerability transfer intensity varies with these conditions. For Hypothesis 4, the relationship between reservoir elevation and generation output is examined for evidence of nonlinear behavior around known operational thresholds. Throughout, the study integrates published quantitative estimates with original data compilation. The resulting analysis is interpretive rather than confirmatory: it aims to characterize the direction, plausibility, and conditions of the proposed mechanisms, not to estimate precise effect sizes or establish statistical causation.

Limitations

Several limitations should be acknowledged. This study is a structured comparative synthesis, not a causal identification design; the associations documented here are consistent with the proposed mechanisms but do not establish causality in the econometric sense. The geographic scope covers the most drought-vulnerable regions but does not capture the full spatial extent of U.S. energy infrastructure risks. Economic impact estimates drawn from the literature employ varying methodologies. The cascading risk analysis, while informed by quantitative evidence, does not employ a fully coupled water-energy simulation model. Future research using panel estimation with quasi-experimental variation or integrated optimization models (e.g., Szinai et al., 2024) could provide more precise quantification and causal grounding for the feedback mechanisms identified here.

4. Results

Drought and hydropower decline (Hypothesis 1)

Consistent with Hypothesis 1, the data indicate significant and heterogeneous drought-induced declines across Western U.S. hydropower facilities. During the 2021 drought, California's hydropower generation fell 48% below the 10-year average (2011-2020) (EIA, 2022), with the most severe impacts at individual facilities: the Edward Hyatt powerplant at Oroville Dam experienced an 81% generation decline and was shut down entirely for the first time since 1967 when Lake Oroville dropped to approximately 640 feet, well below the minimum operating level (EIA, 2022). The Pacific Northwest, characterized by different basin hydrology and larger storage ratios, experienced a 14% decline below the 10-year average, consistent with Hypothesis 1's prediction that decline magnitude varies by basin characteristics.

The Colorado River system illustrates the most severe end of the vulnerability spectrum. Lake Mead dropped to approximately 1,040 feet elevation in mid-2022 (Bureau of Reclamation data), reducing Hoover Dam's effective generating capacity from 2,080 MW to 1,304 MW, a 37% reduction. Power generation in 2023 was approximately half the output of 2000. Lake Powell reached approximately 3,522 feet in March 2023, just 32 feet above the minimum power pool elevation of 3,490 feet. The physical mechanism is direct: hydraulic head at Lake Mead decreased from approximately 590 feet at full pool to approximately 420 feet, a 29% reduction that translates proportionally to power output losses. Wildfire further exacerbates drought impacts on water supply, with Williams et al. (2022b) demonstrating that post-fire watersheds exhibit reduced water yield and impaired water quality for decades. Higher temperatures compound the effect through reservoir evaporation (Bureau of Reclamation estimates suggest 600,000-800,000 acre-feet annually at Lake Mead) and reduced snowpack shifting runoff timing.

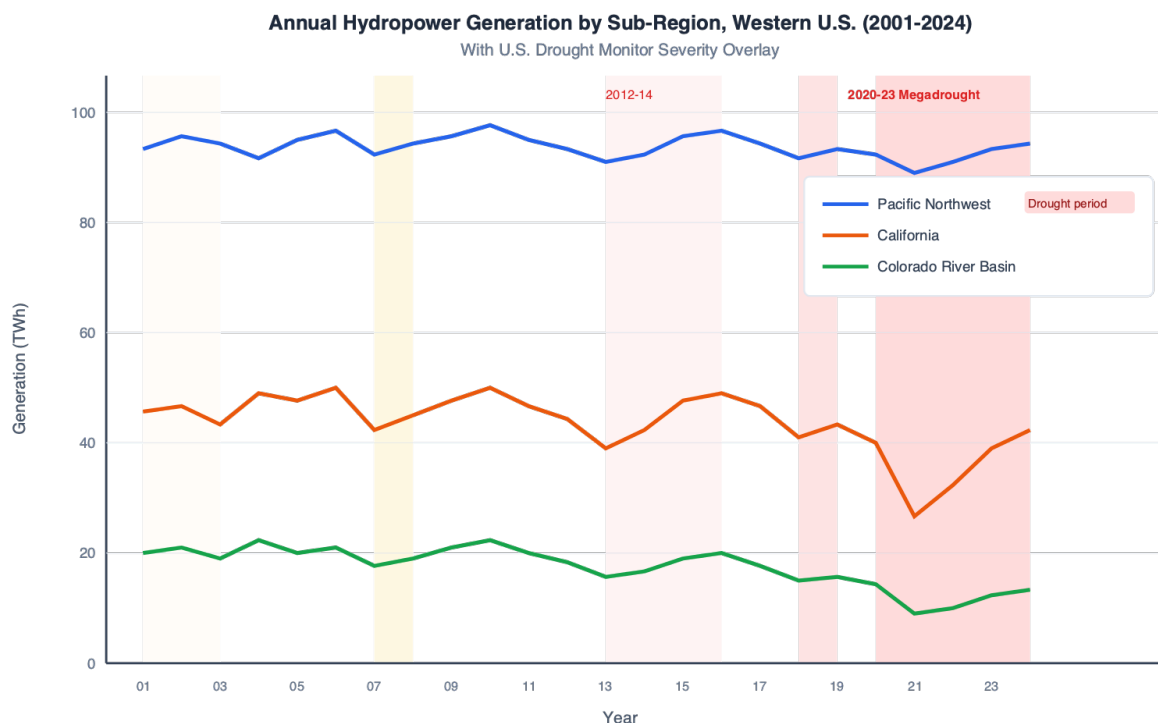


Figure 1. Stylized representation of annual hydropower generation trends by sub-region (California, Pacific Northwest, Colorado River Basin), 2001-2024. Shaded bands indicate periods classified as D3 (Exceptional) or D4 (Extreme) drought by the U.S. Drought Monitor for the corresponding geographic area. California experienced a 48% decline below its 10-year average during the 2021 drought (EIA, 2022); the Pacific Northwest declined approximately 14%. The Colorado River Basin shows a sustained downward trend, with Hoover Dam output approximately halved by 2023 relative to 2000. Generation magnitudes are illustrative of regional trends; precise annual values are available from the EIA Electricity Data Browser (<https://www.eia.gov/electricity/data/browser/>).

Table 1. Drought impacts on major Western U.S. hydropower facilities.

Facility	River	Capacity (MW)	Generation decline	Lowest recent level
Hoover Dam	Colorado	2,080	~50% vs. year 2000	1,040 ft (2022)
Glen Canyon Dam	Colorado	1,320	60-70%	3,522 ft (2023)
Oroville (Hyatt)	Feather	819	81%; shutdown	~640 ft (Aug. 2021)
Grand Coulee	Columbia	6,809	12%	Moderate decline
Shasta	Sacramento	714	46%	~35% capacity (2021)

Hydro-fossil substitution dynamics (Hypothesis 2)

The available evidence is consistent with Hypothesis 2. Using a comprehensive analysis of electricity generation data across the Western Interconnection, Qiu et al. (2023) demonstrated that under extreme drought individual fossil fuel plant generation increases up to 65%, primarily compensating for reduced hydropower output. California’s fossil fuel generation increased approximately 35% during the driest months, with 54% of drought-induced additional generation occurring as transboundary effects in neighboring electricity regions. The same analysis attributes approximately \$20 billion in total monetized damages to this substitution mechanism over 2001-2021. The substitution is predominantly toward natural gas: when California lost

approximately 15-20 TWh of hydropower in 2021, the shortfall was largely filled by gas-fired generation, with EIA reporting corresponding increases in natural gas consumption by the power sector (EIA, 2022). This substitution carries a dual penalty: California’s power sector CO₂ emissions increased in 2021 relative to 2020, consistent with the magnitudes reported by Qiu et al. (2023) for drought-induced emissions, and the additional thermoelectric cooling load placed further demands on water supplies already stressed by the drought driving the hydropower decline. Figure 2 synthesizes these findings schematically, illustrating the general direction and magnitude of the association as documented in the published literature.

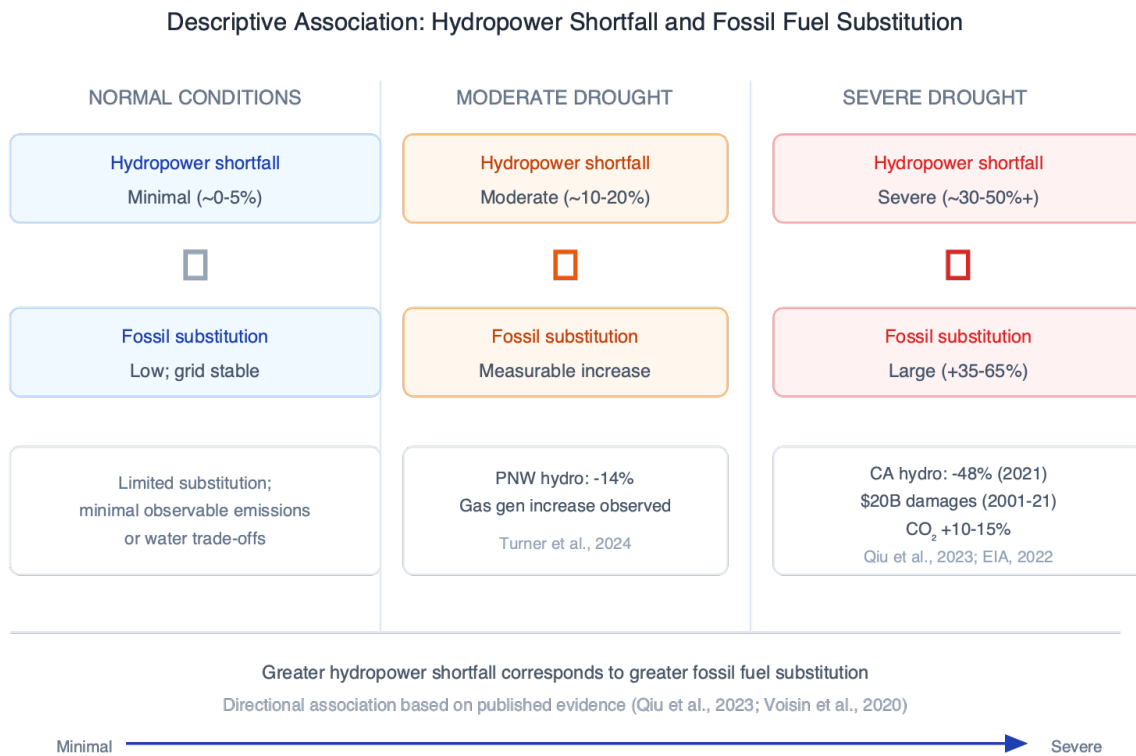


Figure 2. Descriptive association between hydropower shortfall severity and fossil fuel substitution response across the Western U.S. Three scenario columns summarize the observed pattern based on published evidence: under normal conditions, substitution is minimal; under moderate drought (e.g., Pacific Northwest, -14%), gas-fired generation increases measurably; under severe drought (e.g., California 2021, -48%), fossil generation increases by 35-65% with substantial emissions and economic consequences. Magnitudes are derived from Qiu et al. (2023), Turner et al. (2024), and EIA (2022). This figure is a descriptive synthesis and does not represent a statistical model.

Regional heterogeneity and structural conditioning (Hypothesis 3)

Consistent with Hypothesis 3, the severity of cross-sector vulnerability varies systematically with regional characteristics. Regions combining high hydropower dependence with elevated oil and gas water demand and fragmented water governance exhibit the most pronounced vulnerability transfer. California represents the archetype: the San Joaquin Valley hosts both major oil production (Kern County, ~70% of state output) and depends critically on water deliveries that also sustain hydropower generation. When drought reduces State Water Project deliveries simultaneously curtailing hydropower and oil field water supply, the sectors compete directly for the same diminishing resource. In contrast, the Pacific Northwest, where hydropower dominance

is even greater (~60% of generation) but oil and gas presence is minimal, experiences the substitution effect primarily as an export phenomenon: reduced Northwest hydro raises electricity costs and emissions in importing regions rather than creating local water competition.

The Permian Basin presents the inverse case: extreme water stress for oil and gas operations (water demand peaked at 35% of non-mining consumption) with minimal hydropower presence. Here, drought-induced vulnerability operates primarily through the direct water scarcity channel rather than the substitution mechanism, with water procurement costs increasing 3-6 times during the 2011-2014 drought (Scanlon et al., 2017). This regional variation supports the proposition that vulnerability transfer is structurally conditioned: the drought-mediated infrastructure risk transfer mechanism operates most powerfully where hydropower dependence, fossil backup availability, and oil and gas water demand coexist within a shared hydrological system.

Table 2 summarizes the structural characteristics of the four sub-regions examined and classifies the expected intensity of cross-sector vulnerability transfer in each. The classifications are based on the authors’ assessment of the evidence reviewed in Section 2 and the data assembled in Section 3: “hydro dependence” reflects the share of hydropower in regional generation mix; “O&G water demand” reflects published estimates of oil and gas water consumption relative to regional supply; “transfer intensity” is an integrative judgment based on the co-presence of the three structural conditions identified in the theoretical framework (hydropower dependence, fossil backup availability, and oil and gas water demand within a shared hydrological system). These classifications are intended as a comparative heuristic, not as outputs of a formal scoring model.

Table 2. Regional structural characteristics and assessed vulnerability transfer intensity (authors’ classification based on reviewed evidence).

Region	Hydro dependence	O&G water demand	Dominant risk pathway	Transfer intensity
California	High (11-15%)	Moderate (Kern County)	Substitution + water competition	Very high
Colorado River Basin	High (Hoover, Glen Canyon)	Low	Substitution + downstream propagation	High
Pacific Northwest	Very high (60%+)	Very low	Export-driven substitution	Moderate
Permian Basin	Minimal	Very high (35% non-mining)	Direct water scarcity	High (sectoral)

Threshold effects and nonlinear vulnerability (Hypothesis 4)

Available evidence suggests the existence of threshold effects predicted by Hypothesis 4. The relationship between reservoir elevation and power output is not linear: it exhibits inflection points at known operational thresholds where system behavior changes qualitatively. At Hoover Dam, generation declines gradually as Lake Mead falls from full pool (1,221 feet) toward 1,050 feet, but at 1,035 feet, twelve older turbines shut down entirely, causing capacity to drop precipitously from 1,304 MW to 382 MW. This is not a smooth continuation of decline but a regime shift: a 15-foot elevation change triggers an approximately 82% capacity loss. At Glen Canyon Dam, the minimum power pool at 3,490 feet represents an absolute threshold below which generation falls to zero, and current levels (3,522 feet) place the system within 32 feet of this discontinuity.

These facility-level thresholds create system-level nonlinearities. The near-simultaneous approach of both major Colorado River dams toward their critical thresholds in 2022-2023 created compounding effects that the linear framing of “gradual drought impact” fails to capture. The Bureau of Reclamation retained 480,000 acre-feet in Lake Powell in 2022 specifically to protect power pool, reducing downstream releases and thereby accelerating Lake Mead’s decline toward its own threshold. This operational interdependence means that threshold proximity at one facility can trigger or accelerate threshold approach at interconnected facilities, a cascading dynamic that is consistent with complex adaptive systems predictions about infrastructure networks under stress.

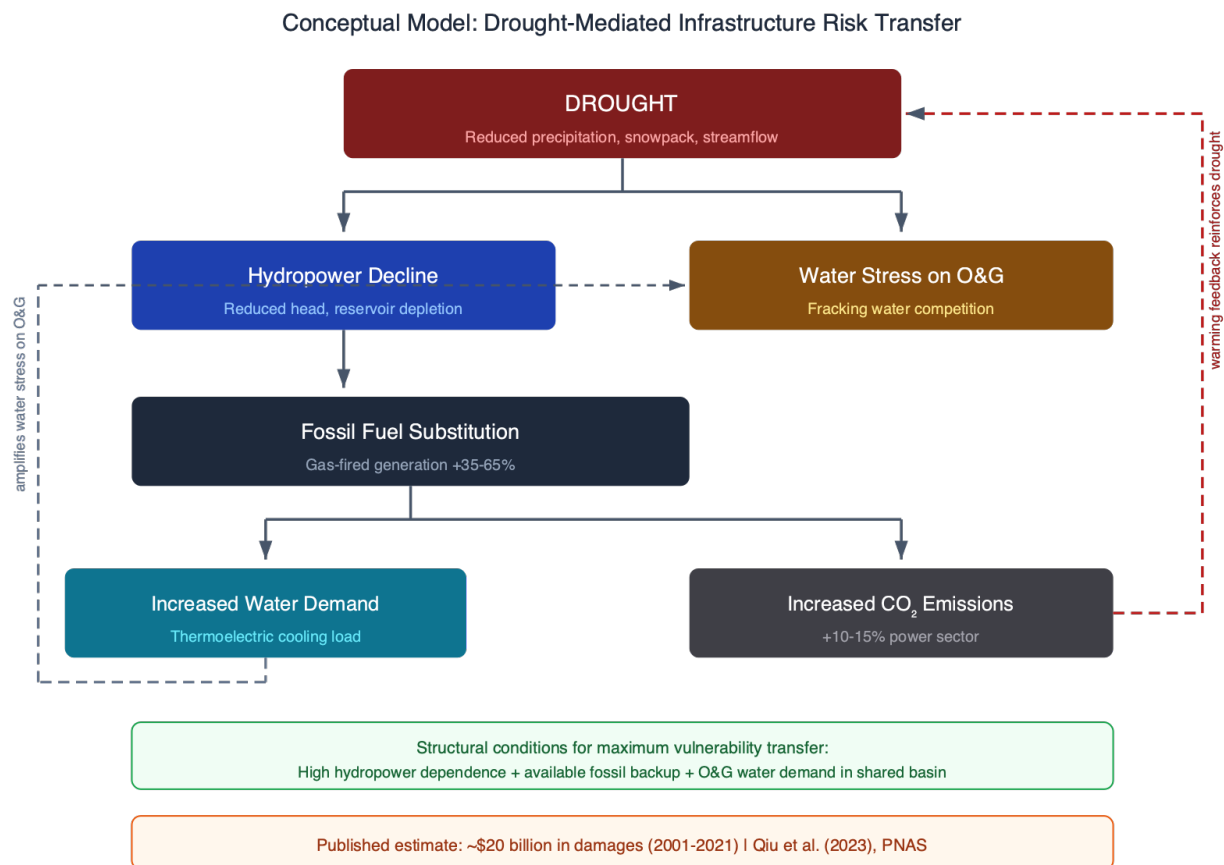


Figure 3. Conceptual model of drought-mediated infrastructure risk transfer. Drought reduces hydropower output and intensifies water stress on oil and gas operations (Row 2). Hydropower shortfalls trigger fossil fuel substitution (Row 3), which increases both water demand for thermoelectric cooling and CO₂ emissions (Row 4). Two feedback pathways operate at the system margins: increased water demand amplifies competition with oil and gas operations (left, dashed), while increased emissions contribute to warming that reinforces drought conditions (right, dashed red). This mechanism operates most acutely where hydropower dependence, fossil backup capacity, and oil and gas water demand converge within a shared hydrological basin. Published estimates attribute approximately \$20 billion in damages to this mechanism over 2001-2021 (Qiu et al., 2023).

Table 3 provides a comparative synthesis of climate vulnerability across the two energy sectors examined in this study. The severity classifications (High, Medium, Low) reflect the authors’ qualitative assessment based on the published evidence reviewed in Section 2. Because different climate hazards affect the two sectors through distinct physical mechanisms, the cross-sector interaction column identifies the primary pathway through which a given hazard may create interdependent rather than independent vulnerability. This table is intended as a conceptual summary to orient discussion of adaptation priorities, not as a quantitative risk ranking.

Table 3. Comparative climate vulnerability synthesis: hydropower vs. oil and gas (qualitative assessment based on reviewed literature).

Climate hazard	Hydropower	Oil & Gas	Primary cross-sector interaction
Drought	High	High	Water competition; generation substitution
Extreme heat	Medium	Medium	Concurrent peak demand stress
Wildfire	Low-Medium	High	Grid disruption amplifies sectoral impacts
Flooding	High	Medium	Post-drought flash flooding risk
Sea level rise	Low	High	Coastal infrastructure concentration
Seasonal shift	High	Low	Supply-demand temporal mismatch

5. Discussion

The assembled evidence is consistent with drought functioning as a system-level stressor whose effects on energy infrastructure are shaped by structural interdependencies rather than operating as parallel, independent impacts on separate sectors. All four hypotheses find directional support in the available record, though each with important qualifications that define the boundaries of the present analysis. The drought-hydropower relationship (Hypothesis 1) is well documented but heterogeneous, mediated by basin hydrology and storage capacity in ways that a comparative synthesis can characterize but not precisely estimate. The substitution effect (Hypothesis 2) is supported by published estimates (Qiu et al., 2023) but exhibits transboundary dynamics that complicate regional attribution. Structural conditioning (Hypothesis 3) is suggested by the regional comparison but would benefit from more granular institutional analysis. Threshold effects (Hypothesis 4) are observable at the facility level, though their system-wide implications require modeling approaches beyond the scope of this study. The observed pattern of gradual stress accumulation followed by abrupt capacity loss is consistent with the resilience framework developed in complex adaptive systems theory (Holling, 1973), where systems absorb perturbation until a critical threshold is crossed, triggering a regime shift (Folke et al., 2004). These patterns warrant further investigation through panel estimation or coupled water-energy simulation models.

The concept of drought-mediated infrastructure risk transfer offers a more precise analytical vocabulary than the prevailing framing of “cascading impacts.” Where previous studies have documented the hydro-fossil substitution phenomenon (Qiu et al., 2023) or modeled water-energy interdependencies (Voisin et al., 2020), the present synthesis suggests that these are not independent phenomena but connected manifestations of a single mechanism: drought triggers a redistribution of risk across sectors through the specific pathway of generation substitution, water competition, and emissions feedback. This mechanism is structurally conditioned, operating most intensely where three factors converge: hydropower dependence, available fossil backup, and oil and gas water demand within the same hydrological system. This suggests that vulnerability assessments conducted at the sectoral level may systematically underestimate total system risk.

A deeper issue concerns the baselines against which vulnerability is assessed. The twentieth-century hydrological record, against which Colorado River allocations were set and hydropower infrastructure was designed, now appears to have been an anomalously wet period in the longer paleoclimate context. If the 1906-1999 average represents a hydrological optimum rather than a normal baseline, then the current “drought” is less an aberration than a return to longer-term mean conditions. This reframing has substantial implications: what appears as climate-induced vulnerability may in part reflect structural overcommitment of water resources based on a historically unrepresentative planning horizon. Infrastructure vulnerability, in this view, is not only produced by climate change but also by the governance assumptions embedded in its original design. The

baseline itself is an institutional artifact: a product of the specific historical period in which allocation rules were codified and infrastructure was scaled. This is a form of what Pauly (1995) termed "shifting baseline syndrome," where each generation accepts the conditions it inherits as normal, obscuring the cumulative magnitude of change.

The policy implications of these findings point toward the inadequacy of sector-siloed governance. Current water management in the western United States treats energy sector water demands independently: hydropower operations fall under the Federal Energy Regulatory Commission, oil and gas water use under state commissions, and thermoelectric cooling under EPA and state environmental agencies. The drought-mediated risk transfer mechanism identified here operates in the gaps between these jurisdictions. As Ostrom (1990) demonstrated for common-pool resources more generally, fragmented governance of shared resources tends to produce outcomes that are individually rational but collectively suboptimal, particularly under conditions of scarcity and uncertainty. Integrated water-energy governance at the basin scale is essential: drought contingency protocols should account for substitution effects across sectors; water allocation frameworks should incorporate projected demand from both hydropower operations and oil and gas production under climate scenarios; and resilience standards should be calibrated against compound events rather than single-hazard scenarios.

Recent assessments of climate change priorities for infrastructure globally confirm that water and energy systems rank among the most urgent sectors requiring coordinated adaptation (Leal Filho et al., 2024). Adaptation strategies must similarly bridge sectoral boundaries. For hydropower, forecast-informed reservoir operations, wide-range turbine runners (already underway at Hoover Dam), and treatment of hydropower as variable rather than firm capacity in grid planning represent promising approaches. For oil and gas, produced water recycling (15-30% in the Permian Basin), brackish water sourcing, and wildfire defensible space requirements around infrastructure address sector-specific vulnerabilities. However, these strategies do not address the cross-sector feedback mechanism. Reducing the substitution effect requires structural changes to the generation portfolio: Szinai et al. (2024) estimated that adapting the Western Interconnection may require up to 110 GW of battery storage and 78 GW of additional solar PV. Even so, rapid renewable expansion alone reduces drought-induced fossil damages by only 5.4% (Qiu et al., 2023), underscoring that technology deployment without governance integration will be insufficient.

The findings also carry implications for how adaptation itself is evaluated. If adaptation in one domain externalizes vulnerability into another, as when produced water recycling reduces direct water withdrawal but does not address the systemic substitution mechanism, then adaptation success measured at the sectoral level may mask continued or redistributed system-level risk. This suggests that adaptation metrics should be evaluated against cross-sector outcomes, not merely sectoral performance indicators. The environmental justice dimensions identified by Gonzalez et al. (2024), showing that wildfire-well interactions disproportionately affect minority communities, further underscore that the distribution of climate risk across infrastructure systems is not merely a technical problem but a governance and equity challenge.

6. Conclusion

This study develops a comparative and empirically informed framework for understanding how drought transfers vulnerability across hydropower and oil and gas systems in the western United States. The analysis indicates that both sectors face significant and potentially escalating climate vulnerabilities, but through distinct mechanisms that interact in ways not captured by sector-specific assessments. Hydropower infrastructure has experienced a cumulative generation decline of 23% since 1980, with extreme drought years causing output reductions of 48-81% at major facilities. Oil and gas operations face intensifying water competition, with per-well demand increasing up to 770% in water-stressed regions where 57% of wells are located.

The central contribution is the identification and characterization of drought-mediated infrastructure risk transfer: drought reduces hydropower, necessitating fossil fuel substitution, which amplifies water demand and carbon emissions, reinforcing the warming that intensifies drought. Published estimates attribute approximately \$20 billion in monetized damages to this mechanism over 2001-2021 (Qiu et al., 2023). The mechanism operates most acutely where hydropower dependence, fossil backup availability, and oil and gas water demand converge within shared hydrological systems. Threshold effects in reservoir levels introduce nonlinear dynamics that accelerate cross-sector stress beyond critical elevations, and the twentieth-century baseline against which infrastructure was designed may itself represent an anomalous hydrological optimum.

These findings underscore the need for a shift from sector-siloed to integrated approaches in energy infrastructure climate risk management. Drought cannot be effectively managed as a collection of parallel sectoral impacts when the risks are demonstrably interconnected through substitution, water competition, and emissions feedback. Integrated water-energy governance, compound event resilience standards, and cross-sector adaptation evaluation metrics are essential. The western United States faces not merely a series of climate impacts on its energy infrastructure, but a systemic transformation of the conditions under which that infrastructure was designed to operate.

Author Contributions

T.N. conceived the study, designed the analytical framework, conducted the literature synthesis and data compilation, interpreted the results, and wrote the manuscript.

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Data Availability

All data analyzed in this study are derived from publicly available sources. Hydropower generation data are available from the U.S. Energy Information Administration Electricity Data Browser (<https://www.eia.gov/electricity/data/browser/>). Reservoir elevation and storage data are available from the U.S. Bureau of Reclamation (<https://www.usbr.gov/>). Drought severity data are available from the U.S. Drought Monitor (<https://droughtmonitor.unl.edu/>). Hydraulic fracturing water use data are compiled from state regulatory agencies and published sources cited in the text.

Conflicts of Interest

The authors declare no conflicts of interest.

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