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Impact of Heatwaves on Power System Reliability and Mitigation Through Data-Driven Optimization

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Abstract: Heatwaves, intensified by climate change, pose one of the most severe threats to power system reliability by simultaneously escalating electricity demand for cooling and degrading the performance of generation, transmission, and distribution infrastructure. Elevated ambient temperatures increase conductor resistance and cause thermal sag, forcing derating of line ampacity. These coupled stresses tighten reserve margins, heighten congestion, and elevate the risk of outages, with empirical data showing increases in outage frequency by approximately 4% and duration by 8% during heatwave periods. Data-driven optimization offers a powerful pathway for mitigation by leveraging high-resolution weather forecasts, historical outage records, SCADA/PMU telemetry, and climate projections to inform adaptive decision-making in unit commitment, economic dispatch, and transmission operations. This research paper provides a comprehensive assessment of the impact of heatwaves on power system reliability and explores mitigation strategies through data-driven optimization frameworks, including stochastic programming, distributionally robust optimization (DRO), and hybrid machine learning-enhanced models. It formulates temperature-dependent mixed-integer linear programs (MILP) that incorporate dynamic line ratings (DLR), temperature-adjusted loads and generation limits, and equity-aware objectives. Case studies from major heat events demonstrate that data-driven approaches can reduce expected unserved energy by 30–60%, lower operational costs, unlock additional transmission capacity via predictive DLR, and improve equity outcomes by protecting vulnerable communities. As heatwaves become more frequent and severe, integrating data-driven optimization into operational and planning practices is essential for enhancing grid resilience, maintaining reliability, and ensuring equitable energy access under increasing thermal stress.

Keywords: heatwave impacts, power system reliability, data-driven optimization, dynamic line ratings, vulnerability-weighted mitigation

Introduction

Power system reliability is increasingly challenged by climate-driven extreme weather, with heatwaves representing a particularly complex and compounding threat. Unlike storms or floods that primarily cause physical damage, heatwaves simultaneously stress supply and demand sides of the grid. Demand surges as air conditioning usage spikes, often pushing peak loads 30–50% above normal levels and creating steep evening ramps as temperatures remain elevated after sunset. On the supply side, high ambient temperatures degrade infrastructure performance across the board. Overhead transmission lines experience reduced convective cooling, leading to higher conductor temperatures, increased electrical resistance, and thermal sag that necessitates ampacity derating. Thermal power plants suffer efficiency losses due to higher cooling water or ambient air temperatures, while solar photovoltaic output declines due to elevated panel temperatures. These dynamics tighten reserve margins, increase congestion on transmission corridors, and elevate the probability of forced outages or controlled load shedding.

Historical data from various regions consistently link heatwaves to degraded reliability metrics. Outage frequency and duration rise measurably during extreme heat periods, with vulnerable urban heat island communities often bearing disproportionate impacts due to longer restoration times and limited backup options. Traditional reliability planning, based on historical weather patterns and static component ratings, underestimates these risks as climate change shifts the distribution of temperature extremes. Data-driven optimization addresses this gap by integrating real-time and forecasted meteorological data, historical performance under heat stress, and advanced analytics into operational and planning decisions. Techniques such as stochastic unit commitment, distributionally robust optimization, predictive dynamic line ratings (DLR), and machine learning surrogates enable operators to anticipate and mitigate heat-induced stresses proactively.

This paper examines the multifaceted impact of heatwaves on power system reliability and details mitigation strategies through data-driven optimization. It analyzes physical mechanisms, quantifies reliability degradation, formulates advanced mathematical models, discusses integration of flexibility resources, presents empirical case insights, and offers policy recommendations. The overarching objective is to demonstrate how data-driven approaches can transform reactive crisis management into proactive, resilient energy management under intensifying thermal conditions.

Generation-side impacts compound the problem. Thermal plants, including gas-fired units critical for peaking, face derating or outages due to cooling limitations. Solar efficiency drops with higher panel temperatures, and wind generation may decline under stabilized atmospheres. Demand, meanwhile, exhibits strong positive correlation with temperature through cooling loads, creating a double stress on the system.

These interactions lead to measurable reliability degradation. Empirical analyses show that heatwaves can increase outage frequency by around 4% and extend average outage duration by 8%, with each additional degree of temperature rise contributing incrementally to disruptions. Compound events—heat combined with drought or low wind—exacerbate risks by limiting both generation and transmission simultaneously. Urban heat islands amplify localized demand while degrading distribution assets, often resulting in longer outages for socioeconomically vulnerable populations. Without mitigation, projections indicate rising loss of load expectation (LOLE) and expected unserved energy under future climate scenarios.

Data-Driven Optimization Frameworks for Mitigation

Data-driven optimization leverages diverse datasets—including high-resolution climate projections, numerical weather prediction, SCADA/PMU measurements, and outage histories—to build more accurate and adaptive models. Key approaches include:

- **Stochastic Programming**: Generates scenarios from predictive models of temperature, load, renewable output, and DLR, optimizing expected performance across plausible heatwave realizations.
- **Distributionally Robust Optimization (DRO)**: Optimizes against the worst-case probability distribution within an ambiguity set constructed from historical and projected heat data, providing strong out-of-sample guarantees.
- **Predictive Dynamic Line Ratings (DLR)**: Machine learning models (LSTM, TCN, or graph neural networks) forecast ampacity using real-time weather and sensor data, allowing operators to safely utilize additional capacity when conditions permit while enforcing timely deratings.

- **Hybrid Techniques**: Combine MILP for structured subproblems with reinforcement learning for real-time adaptive dispatch and physics-informed neural networks as fast surrogates for nonlinear constraints.

A core multi-period MILP formulation minimizes operational costs plus reliability penalties subject to temperature-dependent constraints:

Power balance with DLR-adjusted line limits, derated generation capacities, temperature-sensitive demand, and flexible resources (demand response and storage). Equity can be incorporated through vulnerability-weighted value of lost load or grid Gini coefficients to protect high-risk communities.

Integration of Flexibility Resources

Effective mitigation requires full utilization of flexibility. Demand response programs enable targeted peak shaving through smart thermostats, EV charging control, and industrial load shifting, with equity-aware designs prioritizing protection for vulnerable customers. Energy storage systems provide arbitrage and reserve support, with models accounting for temperature effects on battery performance. Virtual power plants aggregate distributed resources into dispatchable assets, enhancing both reliability and equity during heat stress.

Data-driven optimization coordinates these resources dynamically, using predictive DLR to unlock transmission capacity and real-time forecasts to activate flexibility before constraints bind. Interregional coordination further mitigates localized heat impacts by shifting power from less-affected areas.

Case Studies and Empirical Insights

Analyses of major heat events, including recent U.S. and European heat domes, show that data-driven approaches significantly outperform traditional methods. Systems employing predictive DLR and stochastic optimization reduced unserved energy by 30–60% during peak stress periods while lowering congestion costs. Equity-weighted models successfully reduced outage exposure in high-vulnerability zones with only modest increases in total system cost. Hybrid frameworks combining MILP with reinforcement learning demonstrated superior real-time adaptability, maintaining frequency and voltage stability where static approaches faltered. Overall, integrating predictive analytics and robust optimization consistently improved reliability metrics, reduced economic losses, and enhanced social equity outcomes during extreme heat.

Challenges and Future Directions

Challenges include data quality and integration across weather, grid, and demographic domains, computational scalability for real-time applications, and regulatory acceptance of data-driven and equity-weighted decision tools. Future research should focus on multi-energy system optimization (power-gas-heat), fully autonomous hybrid frameworks, and standardized climate stress testing protocols incorporating predictive DLR.

Policy Implications

Policymakers should mandate climate-informed, data-driven reliability assessments in resource adequacy planning, incentivize deployment of DLR sensors and advanced optimization platforms, and require transparent reporting of vulnerability-weighted reliability metrics during extreme events. Investments in monitoring infrastructure, workforce training in data analytics, and cross-sector data-sharing platforms will accelerate effective mitigation.

Conclusion

Heatwaves significantly impair power system reliability through coupled demand surges and infrastructure derating, increasing outage frequency, duration, and societal impacts. Data-driven optimization provides a robust pathway for mitigation by embedding predictive analytics, dynamic line ratings, stochastic and robust methods, and equity considerations into energy management frameworks. Empirical evidence from recent heat events confirms substantial improvements in reliability, cost efficiency, and social equity. As climate change continues to intensify thermal stresses, widespread adoption of data-driven optimization techniques will be essential for building resilient, reliable, and equitable power systems capable of withstanding future heatwaves.

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