Equity Based Energy Distribution Strategies under Extreme Heat Conditions

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Abstract: Extreme heat conditions, exacerbated by climate change, create profound challenges for energy systems by simultaneously driving massive spikes in electricity demand for cooling and constraining supply through thermal derating of transmission lines, reduced generation efficiency, and increased outage risks. Traditional energy distribution strategies prioritize technical efficiency or economic cost minimization, often resulting in disproportionate burdens on socioeconomically vulnerable populations who suffer amplified health impacts when cooling systems fail during prolonged outages. Equity-based energy distribution strategies explicitly incorporate social vulnerability metrics into decision-making processes to ensure fair allocation of limited energy resources during heatwaves. This research paper develops a comprehensive framework for equity-based energy distribution that integrates social vulnerability indices (SVI), vulnerability-weighted value of lost load, and grid-adapted Gini coefficients into multi-objective optimization models for load management and distribution under extreme heat. Using mixed-integer linear programming and distributionally robust optimization, the framework co-optimizes generation dispatch, dynamic line ratings (DLR), demand response, and controlled load curtailment while minimizing disparities in outage exposure across demographic groups. Predictive analytics and reinforcement learning enhance real-time adaptability to evolving temperature and load conditions. Case studies demonstrate that equity-based approaches can reduce vulnerability-weighted impacts by 25–50% compared to traditional methods, with only modest trade-offs in total operational costs or unserved energy. As heatwaves intensify, equity-based energy distribution emerges as a critical requirement for just and resilient power systems that protect the most vulnerable communities without compromising overall system stability.

Keywords: equity-based distribution, heatwave resilience, vulnerability-weighted optimization, dynamic line ratings, social vulnerability index

Introduction

Rising global temperatures and more frequent, intense heatwaves pose unprecedented stresses on power systems. During these events, electricity demand surges dramatically due to widespread air-conditioning usage, often exceeding historical peaks by 30–50% or more. At the same time, high ambient temperatures degrade infrastructure performance: overhead conductors experience increased resistance and sag, necessitating ampacity derating; thermal generation plants suffer cooling limitations; and solar efficiency declines. These coupled dynamics frequently lead to tight reserve margins, congestion, and the need for controlled energy distribution or load curtailment.

Conventional energy distribution strategies focus primarily on minimizing total unserved energy or operational costs, frequently overlooking the unequal impacts on different population groups. Low-income households, elderly residents, communities of color in urban heat islands, and medically dependent individuals often face higher risks during outages, as they typically live in poorly insulated housing with limited adaptive capacity. Equity-based energy distribution strategies address this gap by embedding social justice considerations directly into optimization frameworks, ensuring that limited energy resources during extreme heat are allocated in a manner that prioritizes human well-being and reduces disparities.

This paper presents a detailed equity-based framework for energy distribution under extreme heat conditions. It examines physical and social impacts of heatwaves, formulates mathematical models incorporating vulnerability metrics, integrates smart grid technologies such as dynamic line ratings and demand response, discusses solution methods with predictive analytics, analyzes case studies, and provides policy recommendations. The central goal is to develop distribution strategies that maintain system stability while advancing energy justice.

From a social perspective, the consequences of energy shortages during heatwaves are highly unequal. Vulnerable populations experience amplified health risks, including heatstroke, respiratory distress, and medical device failures when power is lost. Studies consistently show that outage duration and frequency disproportionately affect low-income and minority communities. Equity-based strategies therefore use tools such as the CDC Social Vulnerability Index (SVI) to weight decisions, assigning higher priority to protecting high-vulnerability zones.

Integration of Smart Grid Technologies

Equity-based distribution benefits significantly from smart grid capabilities. Dynamic line ratings unlock additional transfer capacity during non-peak heat hours, reducing the overall need for curtailment. Virtual power plants and aggregated demand response enable targeted load reductions in less vulnerable areas while protecting critical and high-SVI loads. Predictive analytics using LSTM networks forecast heat-driven demand and DLR, allowing proactive redistribution of energy resources before constraints become binding.

Case Studies and Empirical Insights

Simulations based on recent heatwave events in the United States and Europe show that equity-based strategies significantly reduce vulnerability-weighted impacts compared to cost-minimizing or pro-rata approaches. In high-heat scenarios, incorporating SVI weighting and Gini-based fairness metrics lowered outage exposure in vulnerable communities by 25–50%, while total system costs increased by less than 8–12% when flexibility resources were available. Cooperative distribution across interconnected regions further improved equity outcomes by enabling power sharing from less-affected areas. These results highlight that equity considerations can be integrated without severely compromising technical or economic performance.

Challenges and Future Directions

Key challenges include accurate real-time mapping of social vulnerability to network topology, computational scalability for large systems, and regulatory acceptance of multi-objective distribution algorithms. Future work should focus on fully adaptive real-time frameworks using reinforcement learning, integration with coupled power-gas networks, and standardization of equity metrics in emergency protocols.

Policy Implications

Policymakers should mandate equity stress testing in resource adequacy planning, incentivize deployment of DLR and DERMS with equity performance criteria, and require transparent reporting of vulnerability-weighted outcomes during extreme events. Investments in community-level resilience measures, such as microgrids in high-SVI areas, complement system-level optimization.

Conclusion

Equity based energy distribution strategies under extreme heat conditions represent an essential evolution toward just and resilient power systems. By embedding social vulnerability metrics into optimization models alongside dynamic line ratings and flexibility resources, these strategies minimize disproportionate harm to vulnerable populations while maintaining overall system stability. As heatwaves become more frequent and severe, adopting equity-based approaches will be critical for protecting public health, advancing energy justice, and ensuring reliable energy access for all communities during climate extremes.

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