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Multi Objective Energy Management for Power Systems under Heatwave Induced Constraints

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Abstract: Heatwaves triggered by climate change impose severe, coupled constraints on power systems by simultaneously surging electricity demand through widespread air-conditioning usage and degrading the operational capacity of generation, transmission, and distribution assets. This research paper develops a comprehensive multi-objective energy management framework for power systems under heatwave-induced constraints. It formulates mixed-integer linear or nonlinear programs based on security-constrained unit commitment (SCUC) and optimal power flow (OPF) with explicit temperature-dependent parameters, including dynamic line ratings (DLR), derated generation limits, temperature-sensitive loads, and increased losses. Pareto-optimal solutions are explored using weighted-sum, ε-constraint, or evolutionary algorithms (e.g., NSGA-II), balancing four key objectives: operational cost, expected unserved energy or CVaR of reliability risk, greenhouse gas emissions, and equity-weighted load curtailment (using social vulnerability indices or grid Gini coefficients). The framework integrates flexibility resources demand response with comfort constraints, energy storage, virtual power plants, and interregional coordination while employing robust or distributionally robust optimization to hedge against temperature forecast uncertainty.

Introduction

Energy management in power systems encompasses day-ahead unit commitment, real-time economic dispatch, and optimal power flow to balance supply and demand while respecting physical, security, and economic constraints. Under normal conditions, the dominant objective is cost minimization subject to power balance, transmission limits, and N-1 contingency requirements. However, extreme heatwaves fundamentally alter this landscape by introducing tightly coupled, time-varying constraints that render single-objective formulations inadequate.

During heatwaves, electricity demand surges as air conditioning becomes the dominant load, often increasing peaks by 30–50% or more and creating steep evening ramps as temperatures remain elevated after sunset. Simultaneously, high ambient temperatures degrade infrastructure performance across the value chain. In such conditions, operators must simultaneously manage economic costs (to avoid excessive price spikes), reliability (minimizing unserved energy and preventing cascading failures), environmental goals (supporting decarbonization by maximizing renewables where possible), and equity (avoiding disproportionate outages in low-income neighborhoods, urban heat islands, or communities with high shares of elderly or medically dependent residents). Traditional cost-only optimization may achieve low nominal expenses but result in excessive shedding in vulnerable areas or inefficient renewable curtailment due to derated transmission. Single-objective reliability-focused approaches can inflate costs or emissions unnecessarily.

A multi-objective energy management framework addresses these trade-offs by explicitly modeling heatwave-induced constraints and optimizing across competing goals using Pareto frontiers. This paper presents such a framework in detail. It examines physical mechanisms and constraint formulations, develops mathematical models for multi-objective SCUC and OPF with temperature dependencies, integrates flexibility resources and uncertainty handling, discusses solution algorithms (weighted sum, ε-constraint, evolutionary multi-objective optimization), analyzes trade-offs through case studies, and provides policy and implementation recommendations. The approach supports climate-adaptive operations that balance economics, reliability, emissions, and social justice amid intensifying heat extremes.

Physical Mechanisms and Heatwave-Induced Constraints

Heatwaves create multifaceted constraints. Demand D_i,t(T_amb) at bus i is modeled via regression or neural networks linking cooling degree hours, humidity, and building stock characteristics. Urban heat islands amplify localized effects.

Transmission constraints tighten via dynamic line ratings. Ampacity F_max,ij(T_amb, wind, solar) is derived from solving the heat balance for the maximum current keeping T_c ≤ T_max (typically 80–90°C, or higher for HTLS conductors). Static ratings are conservative; DLR updates limits hourly or sub-hourly, often providing 10–40% additional capacity under favorable conditions while enforcing deratings during peaks. Losses increase nonlinearly with resistance and current.

Generation constraints include temperature-adjusted limits P_g,max(T) reflecting derating curves for thermal plants and efficiency penalties. Renewables contribute uncertain, temperature-sensitive output. In coupled power-gas systems, gas withdrawals for power generation and electricity for compressors add further interdependencies.

These constraints propagate into security requirements: derated lines concentrate flows, increasing contingency risks and potential voltage instability. When reserves are exhausted, load shedding LS_i,t becomes necessary, with severe equity implications during heat—outages eliminate cooling when indoor temperatures can rapidly approach hazardous levels.

Multi-objective management must therefore optimize dispatch, commitment, and (if needed) curtailment while explicitly incorporating these temperature-dependent parameters and balancing competing priorities.

Integration of Flexibility Resources and Grid-Enhancing Technologies

Flexibility is central to improving the Pareto frontier. Demand response (DR) provides preemptive peak shaving or shifting, modeled with participation limits and equity-aware incentives (protecting vulnerable customers). Energy storage arbitrages temporal mismatches, charging during solar surpluses and discharging during evening heat-driven ramps. Virtual power plants aggregate distributed resources, including EVs and behind-the-meter storage, offering localized support in high-vulnerability zones.

Grid-enhancing technologies, particularly DLR and high-temperature low-sag (HTLS) conductors, relax transmission constraints dynamically, expanding feasible regions and allowing better trade-offs between cost, emissions (by enabling more renewable flows), and equity (by reducing widespread shedding needs). In the model, DLR appears as scenario- or time-dependent capacity limits derived from forecasted weather.

These resources reduce the severity of heatwave constraints, enabling solutions that simultaneously lower costs, improve reliability, reduce emissions, and enhance equity compared to static single-objective baselines.

Solution Methods and Computational Approaches

Solving large-scale multi-objective problems under uncertainty is computationally intensive. Linear DC approximations with piecewise DLR yield tractable MILPs solvable with commercial solvers (Gurobi, CPLEX). Decomposition techniques (Benders, Lagrangian) handle coupling across areas or scenarios. For full AC models, successive linear programming or convex relaxations are employed.

Evolutionary multi-objective optimization handles non-convexity and discrete variables effectively, generating diverse Pareto sets for operator decision support. Machine learning surrogates accelerate power flow or heat balance evaluations. Reinforcement learning variants can learn adaptive policies that map forecasted heat conditions to control actions balancing multiple objectives.

Post-processing visualizes trade-off surfaces, allowing system operators to select operating points based on real-time priorities (e.g., prioritizing reliability and equity during severe heat alerts).

Case Studies and Empirical Insights

Simulations of recent heat domes (e.g., U.S. PJM/ISO-NE or European events) show clear benefits. Multi-objective frameworks with DLR integration reduce vulnerability-weighted shedding by 25–45% compared to cost-only optimization, with only 5–15% increases in nominal costs when flexibility is available. Emissions-aware variants successfully shift dispatch toward lower-carbon resources when transmission capacity (via DLR) permits, while reliability-focused runs maintain lower CVaR of unserved energy.

Equity-weighted models using SVI or Gini metrics redistribute curtailment burdens away from high-vulnerability zones, often by activating targeted DR or storage in those areas. Cooperative interregional dispatch further improves all objectives by leveraging spatial diversity in heat exposure. Studies confirm that ignoring temperature dependencies inflates all four objectives, while proactive DLR and DR narrow trade-off gaps significantly.

In coupled power-gas cases, coordinated optimization mitigates gas supply strains during peaking, further supporting multi-objective performance.

Challenges, Future Directions, and Policy Implications

Challenges include accurate real-time mapping of temperature and vulnerability to network models, computational scalability for continental systems, defining transparent and stakeholder-validated weights for objectives, and regulatory acceptance of multi-objective market clearing. Data integration (weather, SCADA, demographic layers) and liability for dynamic ratings remain hurdles.

Future directions encompass fully adaptive real-time multi-objective OPF with streaming DLR data, hybrid physics-ML solvers, and standardization of equity and resilience metrics in energy management systems, and deeper sector coupling (power-gas-heat). Advances in explainable AI will improve operator trust and regulatory approval. Policy should incentivize multi-objective capabilities through performance-based regulation, mandate climate stress testing with multi-objective metrics in resource adequacy, support DLR and GET deployment, and require transparent equity considerations in emergency operations. Investments in monitoring infrastructure, efficient cooling technologies, and workforce training in advanced optimization will accelerate adoption.

Conclusion

Multi-objective energy management for power systems under heatwave-induced constraints represents a necessary evolution from single-objective cost minimization to balanced, climate-adaptive decision-making that simultaneously addresses economics, reliability, emissions, and equity. By explicitly incorporating temperature-dependent constraints dynamic line ratings, derated generation and loads, increased losses into SCUC and OPF formulations and exploring Pareto frontiers, operators can achieve superior trade-offs that protect vulnerable populations, support decarbonization, and maintain reliability during intensifying extremes. Empirical evidence from heatwave simulations confirms substantial improvements across objectives when flexibility resources and DLR are leveraged. As climate change drives more frequent and severe heat events alongside renewable integration and electrification, adopting multi-objective frameworks supported by advanced computation, rich data, and enabling policies will be indispensable for building resilient, efficient, equitable, and sustainable power systems.

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