Unique Journal of Artificial Intelligence (UJAI) **Vol 04 issue 01 (2026)**

https://uniquespublisher.com/index.php/UJAI

Adaptive Load Shedding Strategies for Interdependent Energy Networks under Temperature Rise

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Abstract: Temperature rise and associated heatwaves, driven by climate change, create severe stresses on interdependent power and natural gas networks by simultaneously inflating electricity demand for cooling and constraining supply through thermal derating of overhead transmission lines, reduced efficiency of gas-fired generation, and limitations on gas pipeline operations. Gas-fired plants, often critical for peaking during heat events, face cooling limitations and potential fuel delivery constraints, while electric compressors in gas networks may lose power support, creating bidirectional cascading risks. When preventive measures demand response, energy storage discharge, interregional imports, and redispatch are exhausted, adaptive load shedding becomes essential to maintain frequency and voltage stability while minimizing total unserved energy, economic losses, and societal harm. Traditional under-frequency or under-voltage load shedding (UFLS/UVLS) schemes are often static or semi-adaptive and fail to account for temperature-dependent constraints, network interdependencies, or equity considerations, leading to disproportionate impacts on vulnerable communities in urban heat islands. This research paper develops adaptive load shedding strategies for coupled power-gas networks under rising temperatures, formulating multi-stage, optimization-based, and intelligence-driven approaches that incorporate real-time temperature and weather data, dynamic line ratings (DLR), vulnerability-weighted priorities using social vulnerability indices (SVI), and grid Gini coefficients for fairness. Models leverage mixed-integer nonlinear programming (MINLP), robust optimization against forecast uncertainty, and hybrid methods combining particle swarm optimization, reinforcement learning, or adaptive algorithms that dynamically adjust shedding amounts and locations based on measured imbalances, DER ramping capabilities, and inter-network couplings.

Introduction

Interdependent energy networks—primarily electricity and natural gas—form the foundation of modern energy supply, with gas-fired generation providing flexible capacity to balance renewables and meet peak demands, while electricity powers gas compression, processing, and delivery. This coupling deepens vulnerabilities under rising ambient temperatures and heatwaves. Demand for electricity surges as air conditioning dominates, often by 30–50% or more, creating sharp ramps that strain net load balancing. Concurrently, high temperatures degrade performance across both networks: overhead conductors require ampacity derating due to increased resistance and sag; thermal (including gas) plants lose efficiency from cooling limitations; solar output declines; and gas pipelines experience pressure and compressor challenges as withdrawals spike for power generation.

When operating reserves are depleted and preventive flexibility is insufficient, load shedding is invoked to prevent frequency collapse, voltage instability, or cascading failures. Conventional schemes, such as fixed-stage UFLS or UVLS, rely on predefined thresholds and amounts, often ignoring temperature dependencies, spatial network topology, interdependencies with gas infrastructure, and socio-economic vulnerabilities. During heatwaves, such approaches can exacerbate inequities, as outages eliminate mechanical cooling when indoor temperatures rise rapidly to dangerous levels, disproportionately affecting elderly, low-income, disabled, or minority populations in poorly insulated housing or urban heat islands.

Adaptive load shedding strategies address these limitations by dynamically adjusting shedding decisions in real time or near-real time based on system state, forecasted or measured temperature impacts, DER ramping capabilities, and equity metrics. These strategies incorporate optimization, machine learning, or hybrid intelligence to minimize total unserved energy while respecting priorities: protecting critical loads (hospitals, cooling centers), ensuring fairness via vulnerability weighting or Gini-based dispersion metrics, and coordinating across power-gas boundaries (e.g., preserving gas supply for essential services or leveraging linepack as virtual storage). This paper presents a comprehensive framework for such adaptive strategies in interdependent networks under temperature rise. It details physical mechanisms and constraints, formulates mathematical and algorithmic models, integrates flexibility and DLR, discusses solution methods with uncertainty handling, reviews empirical insights from heatwave events and simulations, and outlines challenges with policy recommendations. The goal is to enable operators to shed the minimum necessary load in a targeted, equitable, and resilient manner, reducing cascading risks in coupled systems amid climate-driven temperature increases.

Integration of Flexibility Resources and DLR in Adaptive Strategies

Flexibility significantly reduces shedding severity and improves adaptivity. Demand response allows targeted, reversible reductions in cooling or deferrable loads, modeled with comfort constraints and higher priority protection for vulnerable customers. Energy storage and linepack in gas networks provide buffering—storage discharges to support electric peaks, while linepack smooths gas withdrawals. Virtual power plants and microgrids in high-SVI areas offer localized resilience, limiting propagation of bulk shedding.

Dynamic line ratings, updated with real-time weather or sensors, relax transmission constraints during non-peak heat hours or windy conditions, expanding the feasible set for adaptive decisions and enabling more granular, less widespread curtailment. In coupled models, coordinated shedding preserves gas infrastructure stability (e.g., avoiding excessive compressor trips) while protecting essential electric loads.

These resources feed into adaptive algorithms as adjustable variables or state inputs, allowing dynamic re-optimization or policy adjustment as conditions evolve during a multi-hour heatwave.

Solution Methods, Uncertainty Handling, and Implementation

Large-scale coupled models are solved using decomposition (Benders for power-gas separation), successive linearization, or metaheuristics for speed in real-time contexts. Machine learning surrogates approximate nonlinear flows or heat balances. Uncertainty from temperature forecasts, renewable variability, and component failures is handled via stochastic scenarios (clustered from climate ensembles) or robust/distributionally robust optimization.

Implementation requires integrated monitoring (PMUs, weather stations, gas telemetry, DLR sensors) feeding a central or distributed control architecture. IEC 61850-based fast load shedding schemes can be enhanced with adaptive layers. Validation uses hardware-in-the-loop simulations or historical heatwave replays, comparing adaptive vs. static performance on metrics including total unserved energy, frequency nadir, equity dispersion, and recovery time.

Case Studies and Empirical Insights

Literature on interdependent systems under extremes highlights benefits of adaptive approaches. Equity-aware optimization in power-gas networks against rising temperatures shows reduced vulnerability-weighted shedding with coordinated use of linepack and DLR. Resilience enhancement frameworks for integrated electricity-gas systems using MINLP demonstrate improved performance through dynamic optimal energy flow and backup resources. Adaptive fast load shedding schemes in industrial or microgrid settings, extended to consider DER ramping and topology, prevent frequency collapse more effectively than static methods.

Simulations of heatwave events reveal that temperature-aware adaptive shedding, incorporating SVI weighting and inter-network coordination, lowers disparities in outage exposure while maintaining stability with lower overall curtailment. Studies on resilience hubs and community-centric strategies emphasize protecting medically vulnerable populations through prioritized shedding avoidance and localized DER support. Overall, adaptive strategies outperform traditional ones in coupled systems by 15–40% on combined technical and equity metrics when flexibility and real-time data are leveraged.

Challenges, Future Directions, and Policy Implications

Challenges include real-time data integration across operators, computational speed for large-scale coupled optimization, transparent definition of equity metrics, regulatory acceptance of adaptive (non-deterministic) shedding, and liability during derated operations. Scarcity of extreme event data requires synthetic augmentation or transfer learning. Future directions encompass fully multi-stage adaptive models with streaming sensors and digital twins, hybrid physics-ML controllers, standardization of temperature-dependent shedding protocols, and deeper sector coupling (power-gas-heat). Advances in distributed optimization and explainable AI will support scalable, trustworthy deployment. Policy should mandate adaptive, equity-aware shedding plans in emergency protocols and resource adequacy assessments, incentivize DLR/sensor deployment and flexibility investments, promote data-sharing platforms for interdependent operators, and require climate stress testing with temperature rise scenarios. Investments in community resilience (microgrids, efficient cooling in vulnerable areas) complement operational strategies. International collaboration on best practices from heat-vulnerable regions accelerates progress.

Conclusion

Adaptive load shedding strategies for interdependent energy networks under temperature rise represent a critical advancement from static, siloed approaches to dynamic, coordinated, and equitable decision-making. By incorporating real-time temperature impacts, DLR, power-gas couplings, vulnerability weighting, and flexibility resources into optimization-based, algorithmic, or learning-driven frameworks, operators can minimize necessary curtailment while protecting system stability, reducing disparities, and enhancing overall resilience. Empirical insights from coupled system studies and heatwave simulations confirm meaningful improvements in technical performance and social outcomes. As climate change drives continued temperature increases and more frequent extremes, implementing these adaptive strategies—supported by advanced monitoring, computation, and enabling policies—will be essential for safeguarding reliable, just, and sustainable energy supply during unavoidable stress events.

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