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Research Article

Intelligent Cost Optimization in Hybrid Electricity-Gas Microgrids Considering Distributed Generation and Energy Storage

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Extended Abstract:
The transition towards a decarbonized and resilient energy future has necessitated a paradigm shift from traditional, siloed energy systems to integrated, multi-carrier frameworks. Central to this evolution is the hybrid electricity-gas microgrid, which leverages the synergistic relationship between power and natural gas networks to enhance operational flexibility, economic efficiency, and the integration of renewable energy sources (RES). The research paper by Behnia et al. addresses a critical gap in the existing literature: the lack of a robust, comprehensive, and realistic optimization framework that can simultaneously manage the complex interdependencies of these dual-energy systems under the pervasive uncertainty of real-world market conditions. The paper presents a novel, intelligent cost optimization model for hybrid electricity-gas microgrids that integrates distributed generation (DG), energy storage systems (ESS), and a sophisticated treatment of market price and renewable generation uncertainties.
The core objective of the proposed framework is threefold: to minimize the total operational cost of the microgrid, to maximize the utilization of clean, renewable energy, and to enhance the system's robustness against unpredictable fluctuations in both energy supply and market prices. To achieve this, the authors develop a hybrid optimization model that combines Mixed-Integer Linear Programming (MILP) with Distributionally Robust Chance Constraints (DRCC). The MILP component provides a computationally tractable and globally optimal solution for the complex decision-making process involving the on/off status of generators, power dispatch, energy storage scheduling, and load curtailment. Meanwhile, the DRCC methodology is employed to explicitly model and manage the inherent uncertainties, particularly the volatile nature of electricity and gas market prices, as well as the stochastic output of photovoltaic (PV) and wind turbine (WT) units. This combination ensures that the optimal scheduling decisions are not only cost-effective but also highly reliable, maintaining system feasibility with a user-defined high probability (confidence level) even when faced with the most adverse realizations of uncertainty within a given ambiguity set.
A key strength of the model is its realistic representation of the energy market structure. It is formulated within a two-stage market framework, comprising a day-ahead (DA) market and a real-time balancing (RTB) market. In the first stage, the microgrid operator makes its primary scheduling decisions—such as the commitment of its dispatchable units (microturbines and fuel cells), the planned charge/discharge schedule for its battery energy storage system (BESS), and its energy bids to the DA market—based on forecasts of renewable generation and market prices. In the second stage, after the actual (realized) conditions are known, any imbalance between the scheduled and actual

power is settled in the RTB market at a potentially much higher cost. This structure creates a powerful economic incentive for the optimizer to create a robust initial schedule that minimizes its exposure to the expensive and volatile real-time market, thereby reducing its financial risk.

The physical model of the hybrid microgrid is equally comprehensive. It includes a diverse portfolio of energy assets: dispatchable units such as microturbines (MTs) and fuel cells (FCs) that consume natural gas to generate electricity; non-dispatchable renewable sources in the form of PV and WT; a Battery Energy Storage System (BESS) for temporal energy shifting; and a mix of loads, including both critical (non-interruptible) and flexible (interruptible) demand. The model captures the critical bi-directional coupling between the electricity and gas networks: the dispatchable generators act as the primary link, converting gas into power. Their gas consumption is directly modeled as a function of their electrical output, which in turn affects the gas network's pressure and flow dynamics. This integrated modeling is essential, as it allows the optimizer to make truly coordinated decisions, such as using stored renewable energy to reduce gas consumption during periods of high gas prices, or conversely, using cheap gas to generate power when electricity prices are high.

The performance of the proposed framework is rigorously evaluated on a simulated hybrid microgrid over a 24-hour horizon. The results are presented through a direct comparison between the "optimal" scenario, which uses the full MILP-DRCC model, and a "non-optimal" baseline scenario that lacks the integrated, robust, and coordinated features of the proposed approach. The findings are highly compelling and quantify the significant benefits of the intelligent optimization strategy. The primary economic benefit is an 18% reduction in total operational cost. This substantial saving is achieved through a combination of factors: more efficient dispatch of generators, strategic use of the BESS to arbitrage between low and high electricity price periods, and, crucially, a drastic reduction in reliance on the expensive real-time market.

This last point is quantified by a 55% reduction in the deviation from the day-ahead market schedule. By making a more robust and accurate initial schedule that accounts for uncertainty, the microgrid avoids the large, costly imbalances that would otherwise occur. From a technical and sustainability perspective, the model also delivers outstanding results. The framework enables a utilization rate of renewable energy sources exceeding 95%, meaning that almost all the clean energy generated by the PV and WT units is consumed by the microgrid's loads or storage, rather than being curtailed and wasted. This high penetration of renewables is made possible by the operational flexibility provided by the BESS, the dispatchable gas units, and the interruptible loads, which together act as a buffer to absorb the intermittency of solar and wind.

Furthermore, the model significantly improves the quality of service for end-users. By intelligently managing its resources, the microgrid is able to meet a greater portion of its demand, leading to a 27% reduction in load curtailment. The BESS plays a particularly important role here, as it can discharge stored energy during peak demand hours to prevent the need for shedding flexible loads. The paper also includes a detailed analysis of the individual contributions of each model component, such as the DRCC's role in mitigating market risk and the coordinated electricity-gas planning's role in reducing overall system losses and costs.

In conclusion, this research provides a significant contribution to the field of multi-energy system management. The proposed MILP-DRCC framework is not only theoretically sound but also highly practical and actionable. Its modular structure allows for straightforward extension to include other energy carriers, such as heating and cooling, making it a versatile and forward-looking solution for the design and operation of future smart, integrated energy systems. The quantified benefits—lower costs, higher renewable integration, improved reliability, and enhanced market resilience—demonstrate its clear potential for real-world implementation in complex energy hubs, such as industrial complexes, commercial districts, or smart communities, where the efficient and robust management of multiple energy vectors is paramount.

Keywords: Hybrid microgrid, Energy hub, Robust planning, Cost optimization, Energy storage, DRCC, Renewable energy sources

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