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Operational Characteristics and Energy Efficiency Analysis of Integrated Energy Systems for Urban Applications

With accelerating urbanization and the transition of energy structures, integrated energy systems (IES) have become essential for providing reliable and efficient energy services in cities, while also facing challenges related to high energy consumption, emissions, and operational complexity. IES typically integrate electricity, heating, cooling, and renewable energy sources, achieving high energy efficiency through multi-energy coupling, intelligent scheduling, and demand response. Understanding their operational characteristics and conducting energy efficiency analysis are crucial for optimizing system design, enhancing operational performance, and supporting urban low-carbon development goals.

The operational characteristics of urban IES are influenced by multiple factors, including fluctuations in energy supply and demand, uncertainty in renewable generation, time-varying load profiles, and equipment performance characteristics. The interactions among multiple energy carriers and dynamic energy flows make it difficult to accurately evaluate system efficiency and stability using traditional single-energy or static analysis methods. Furthermore, urban energy systems must balance economic, reliability, and environmental considerations over long-term operation, increasing the complexity of energy efficiency assessments. Therefore, a modeling and evaluation framework tailored to urban IES is necessary to provide scientific support for planning and operation.

This study proposes a systematic method for analyzing the operational performance of urban IES. A multi-energy flow model incorporating electricity, heating, cooling, and renewable energy coupling is developed to simulate energy allocation, operational efficiency, and device coordination under various operating conditions and load scenarios. Energy efficiency indicators and performance evaluation metrics are introduced to quantify system performance across different operational modes. Case studies of representative urban energy systems demonstrate the method's effectiveness and assess the impact of operational strategies on overall energy efficiency.

The results indicate that the proposed approach can comprehensively reveal operational characteristics and identify energy efficiency bottlenecks in urban IES, providing engineering insights for system design optimization, operation management, and policy support. This research contributes theoretical and methodological support for developing urban energy systems that are efficient, low-carbon, and sustainable.