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Robustness Assessment Methods for Sustainable Energy Systems under Long-Term Operation

Driven by energy transition and sustainability goals, sustainable energy systems are increasingly deployed in electricity, heating, and integrated energy supply applications. Compared with conventional energy systems, sustainable energy systems are characterized by multi-energy coupling, distributed structures, and high operational uncertainty. Their long-term performance depends not only on short-term efficiency but also on cumulative effects such as equipment aging, environmental changes, and load fluctuations. Therefore, systematic robustness assessment under long-term operation is essential to ensure safe, stable, and efficient system performance.

Robustness in sustainable energy systems refers to the ability to maintain functionality and performance in the presence of external disturbances and internal uncertainties. Over long-term operation, performance degradation, renewable generation variability, and evolving demand patterns can accumulate, potentially leading to efficiency losses and increased operational risks. Traditional performance evaluation methods typically focus on short-term or steady-state conditions, making them inadequate for capturing system adaptability and risk exposure over extended time horizons. Consequently, robustness assessment methods that incorporate temporal dynamics and uncertainty are required.

This study proposes a robustness assessment methodology tailored to sustainable energy systems under long-term operation. A system modeling framework that accounts for equipment degradation, operating condition variations, and external disturbances is developed to analyze long-term performance evolution. Robustness indicators are introduced to quantitatively evaluate the system’s ability to maintain key performance metrics under different disturbance scenarios. Case studies of representative sustainable energy systems demonstrate the effectiveness of the proposed method in identifying system vulnerabilities and supporting operational optimization.

The results provide scientific support for long-term planning, operation management, and risk mitigation of sustainable energy systems. This research offers an engineering-oriented assessment tool for enhancing the reliability and sustainability of energy systems operating under complex and uncertain conditions.