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Integrated Modeling and Simulation Analysis of Multi-Scale Sustainable Energy Systems

Driven by global energy transition and sustainability goals, energy systems are evolving toward multi-energy coupling, distributed deployment, and intelligent operation. Sustainable energy systems typically integrate renewable energy generation, energy storage, conversion units, and end-use energy consumers, involving processes across multiple temporal and spatial scales. These multi-scale characteristics pose significant challenges for conventional single-scale modeling approaches, highlighting the need for integrated modeling and simulation analysis of multi-scale sustainable energy systems.

Multi-scale energy systems exhibit high complexity in terms of device-level dynamic responses, system-level energy scheduling, and regional energy balancing. Device-level models focus on transient behavior and control strategies, whereas system- and regional-level models emphasize energy flow distribution, load matching, and overall efficiency. Ignoring interactions among different scales may lead to inaccurate simulation results and suboptimal design or operational decisions. Therefore, developing integrated modeling frameworks that coordinate different temporal and spatial scales is critical for accurately analyzing sustainable energy systems.

This study proposes an integrated modeling and simulation methodology for multi-scale sustainable energy systems. A hierarchical modeling framework is established, incorporating device-level dynamic models, system-level energy balance models, and regional operational constraints, enabling information exchange and coordinated simulation across scales. Multi-scenario simulations are conducted to evaluate system performance under renewable energy fluctuations, load variations, and energy storage dispatch strategies. The results demonstrate that the proposed approach effectively captures the impact of multi-scale coupling on system stability, energy efficiency, and operational flexibility.

The findings provide engineering-oriented tools for planning, design, and operation optimization of sustainable energy systems. This research supports the development of integrated energy systems, microgrids, and regional energy planning, contributing to efficient, reliable, and intelligent sustainable energy infrastructures.