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Synergistic Optimization Methods for Resource–Energy–Environment Coupled Engineering Systems

In the context of sustainable development and low-carbon transitions, the interconnections among resource, energy, and environmental systems have become increasingly complex. Traditional engineering optimization approaches focusing on single objectives or isolated subsystems are no longer sufficient to address the challenges of modern industrial and urban systems. Resource consumption, energy conversion, and environmental emissions are closely interrelated, and optimization in one component may lead to efficiency losses or environmental risks at the system level. Therefore, synergistic optimization of resource–energy–environment (REE) coupled engineering systems is essential for improving overall system performance and sustainability.

REE coupled engineering systems typically involve multiple energy carriers, diverse resource inputs, and stringent environmental constraints. Their operational characteristics include multi-objective trade-offs, multi-scale interactions, and strong nonlinearity. In practical applications, improving resource utilization efficiency may increase energy demand, while optimizing energy systems can introduce new environmental impacts. These complex interactions limit the effectiveness of conventional local optimization strategies and highlight the need for integrated methods that simultaneously consider resource efficiency, energy performance, and environmental outcomes.

This study proposes a system-level synergistic optimization methodology for REE coupled engineering systems. A unified modeling framework is developed to represent resource inputs, energy conversion processes, and environmental emissions, enabling the analysis of coupling mechanisms among subsystems and their influence on system performance. Multi-objective optimization techniques and operational constraints are incorporated to construct an optimization model that balances resource efficiency, energy utilization, and environmental performance. The proposed approach is validated through representative engineering case studies, demonstrating its effectiveness in enhancing overall system performance while reducing resource consumption and environmental burdens.

The findings provide a systematic and engineering-oriented approach for the comprehensive optimization of complex systems. This research offers valuable theoretical and practical insights for planning and operating industrial parks, urban infrastructure, and integrated energy systems, supporting the transition toward efficient, low-carbon, and sustainable engineering solutions.