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Synergistic Optimization of Energy Utilization and Environmental Performance from an Engineering Systems Perspective

With the advancement of sustainable development and low-carbon transition strategies, both energy utilization efficiency and environmental performance have become critical evaluation metrics in engineering system design and operation. Modern energy engineering systems are under pressure not only to improve energy efficiency but also to reduce carbon emissions and environmental impacts. Traditional optimization approaches often focus on a single objective, such as maximizing energy efficiency or minimizing emissions, neglecting the complex coupling between energy utilization and environmental performance. This may result in local optimization rather than overall system optimality. Therefore, a systems engineering perspective for synergistically optimizing energy utilization and environmental performance is essential for enhancing overall system sustainability.

Engineering systems typically involve multiple energy carriers, diverse equipment, and complex operating conditions, where energy flows, material flows, and emissions are tightly coupled. Conflicts and synergies exist among different optimization objectives. For example, increasing energy efficiency may lead to higher local emissions or equipment load, while strict emission control could reduce energy utilization. Addressing such multi-objective, multi-constraint challenges requires system-level synergistic optimization models that integrate energy efficiency, environmental impacts, and operational constraints to provide actionable optimization strategies.

This study proposes a system-oriented methodology for synergistic optimization of energy utilization and environmental performance. By constructing system-level models of energy flows and emissions, the impacts of different operational strategies on energy efficiency and environmental indicators are quantified. Multi-objective optimization techniques are then applied to coordinate system operation. Case studies of representative engineering systems are conducted to validate the effectiveness of the proposed approach in balancing energy efficiency and environmental performance, and to identify key influencing factors and optimization pathways.

The results demonstrate that the proposed synergistic optimization method can achieve a balance between energy efficiency improvement and environmental

performance enhancement while meeting functional and safety requirements. This research provides scientific guidance for engineering system design, operational optimization, and policy support, promoting the development of efficient, low-carbon, and sustainable engineering systems.