Quantum Optimization of Energy Consumption in

Flexible Manufacturing Systems Integrating Renewable Power Sources

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***Abstract*—As modern manufacturing transitions toward flexible and energy-adaptive production environments, optimizing energy consumption has become essential for achieving operational sustainability and aligning with global decarbonization goals. Traditional optimization techniques often struggle with the nonlinear, multi-objective, and stochastic nature of energy flows in flexible manufacturing systems, especially when integrating intermittent renewable energy sources such as solar and wind. This study proposes a quantum-enhanced optimization framework leveraging quantum annealing, variational quantum algorithms, and hybrid quantum–classical solvers to minimize energy usage while maintaining production throughput and scheduling feasibility. The approach formulates energy allocation, load balancing, and production scheduling as combinatorial optimization problems that benefit from quantum parallelism and high-dimensional state exploration. Simulations conducted on benchmark manufacturing models demonstrate that the quantum-enabled framework improves peak-load reduction, enhances renewable utilization rates, and reduces overall energy consumption by up to 22% compared to classical baselines. These results indicate the transformative potential of quantum optimization in enabling cleaner, more resilient, and sustainably powered manufacturing ecosystems.**

Manufacturing systems are undergoing a rapid evolution driven by the increasing demand for flexibility, sustainability, and energy efficiency. Flexible manufacturing systems (FMS) are designed to adapt to variable product mixes, fluctuating workloads, and complex scheduling constraints—yet these capabilities often come with increased energy demands and operational complexity [4]. As industries strive to align production with environmental sustainability targets and carbon reduction frameworks, integrating renewable energy sources into manufacturing has emerged as a promising—but operationally challenging—strategy [2]. The intermittent and variable nature of renewables introduces uncertainty in energy availability, complicating real-time scheduling, machine utilization planning, and load balancing across production lines [3].

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Classical optimization approaches, including linear programming, evolutionary algorithms, and heuristic scheduling methods, have contributed significantly to energy-aware manufacturing [8]. However, these methods frequently encounter scalability limitations when modeling the high-dimensional interactions among energy consumption patterns, machine states, and renewable power fluctuations. The combinatorial explosion inherent in such systems results in suboptimal solutions or prohibitive computation times, particularly for near real-time applications in Industry 4.0 environments [5].

Quantum computing presents a promising paradigm shift for addressing these challenges.

