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Optimization of hybrid renewable energy systems using quantum-inspired algorithms

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Abstract
The study explores the application of quantum-inspired optimization algorithms (QIOA) for enhancing the performance, efficiency, and reliability of hybrid renewable energy systems (HRES) comprising photovoltaic (PV), wind, and battery storage components. Conventional metaheuristic algorithms, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE), often struggle with complex, nonconvex optimization landscapes and uncertain renewable variability. To address these limitations, a quantum-inspired optimization framework was developed that integrates quantum principles superposition, tunneling, and probabilistic rotation operators within classical computational structures. Using a simulated hybrid microgrid model in MATLAB/Simulink with stochastic solar and wind inputs, the QIOA approach was benchmarked against classical methods for key performance indicators, including Levelized Cost of Energy (LCOE), Net Present Cost (NPC), reliability, and renewable energy fraction.

Results from fifty independent simulations revealed that QIOA significantly reduced both LCOE and NPC while improving convergence rate and reliability (≈99%), outperforming traditional algorithms across all tested metrics. Statistical evaluation using bootstrap confidence intervals and Wilcoxon signed-rank tests confirmed the robustness and significance of these improvements. Additionally, QIOA demonstrated superior resistance to environmental and load uncertainties, maintaining consistent performance under stress conditions. These outcomes validate the hypothesis that quantum-inspired optimization offers a more powerful, globally convergent, and computationally efficient method for HRES optimization than existing metaheuristics.

The research provides both theoretical and practical contributions: it establishes the foundation for integrating quantum computation principles into classical energy optimization and proposes real-world applications for energy planners, microgrid operators, and smart grid designers. The findings highlight the feasibility of incorporating QIOA into renewable energy management platforms, thereby promoting the design of sustainable, cost-effective, and resilient energy infrastructures. This study ultimately demonstrates that quantum-inspired computation represents a promising pathway toward intelligent, uncertainty-resilient optimization for next-generation renewable energy systems.

Keywords: Quantum-inspired optimization, hybrid renewable energy systems, energy management, metaheuristic algorithms, microgrid optimization, levelized cost of energy, net present cost, renewable fraction, computational efficiency, robust optimization, smart grids, quantum-inspired algorithms, photovoltaic-wind systems, energy storage, sustainable power systems

Introduction

In recent years, the integration of multiple renewable energy sources, energy storage, and hybrid configurations has become central to efforts aimed at decarbonizing power systems and enhancing energy security. The intermittent and stochastic nature of sources such as solar and wind poses significant challenges for stability, reliability, and cost optimization in Hybrid Renewable Energy Systems (HRES) [1, 2]. Conventional metaheuristic and evolutionary algorithms (e.g. particle swarm optimization, genetic algorithms) have been extensively applied to optimally size, dispatch, and schedule HRES, but they often struggle with large, highly nonlinear, nonconvex search spaces and may become trapped in local optima or suffer slow convergence [3, 4]. Meanwhile, inspiration from quantum computing has led to the development of quantum-inspired algorithms (e.g. quantum annealing, quantum-inspired genetic algorithms, quantum-inspired swarm algorithms), which mimic quantum phenomena such as tunneling or superposition in classical architectures to potentially achieve stronger global search capabilities [5-7]. Despite this promise, application of quantum-inspired methods to HRES remains relatively nascent, and a systematic, comparative study is lacking.

Thus, the problem addressed in this research is: can quantum-inspired optimization algorithms outperform classical strategies in the design and operational optimization of hybrid renewable energy systems, in terms of cost, reliability, and computational efficiency? More specifically, can these algorithms navigate multimodal fitness landscapes and uncertain input conditions (e.g. fluctuating renewable output, variable load) more robustly than classical counterparts? The objectives of this study are: (i) to develop one or more quantum-inspired optimization algorithms tailored for HRES (e.g. combining quantum tunnels or probabilistic flip operators), (ii) to model a representative hybrid renewable energy system with storage, constraints, and uncertainty, (iii) to benchmark performance against classical metaheuristics on metrics such as levelized cost of energy (LCOE), reliability, and computational time, and (iv) to analyze sensitivity and robustness under varying renewable and load scenarios. The hypothesis is that quantum-inspired optimization will yield statistically significant improvements in global optimum attainment, computational convergence speed, and solution robustness compared to classical algorithms in the context of HRES optimization.

Material and Methods

Materials

The study focuses on the modeling and optimization of a Hybrid Renewable Energy System (HRES) consisting of Photovoltaic (PV) panels, wind turbines, and a battery energy storage system. The simulated hybrid setup was modeled to represent an isolated microgrid configuration designed to serve a medium-sized community with variable load and stochastic renewable resources. Input meteorological data such as solar irradiance, ambient temperature, and wind speed were obtained from the National Renewable Energy Laboratory (NREL) database to ensure the realism of temporal variability [1, 2]. System components were sized based on standardized technical specifications: monocrystalline PV modules of 320 W rated capacity, variable-speed wind turbines rated at 3 kW each, and lithium-ion battery units with an energy density of 200 Wh/kg [3, 4].

All simulations were conducted in a MATLAB/Simulink environment integrated with Python-based optimization routines. Cost parameters, including capital, operation, and maintenance expenses, were derived from current literature and verified through HOMER Pro data sets [5, 6]. The Levelized Cost of Energy (LCOE), total net present cost (NPC), and renewable fraction were considered as primary performance indicators [7]. A standard time step of one hour was used to capture daily and seasonal variations in renewable generation. The model incorporated probabilistic uncertainty in solar and wind profiles using a Gaussian random process to simulate stochastic environmental behavior [8, 9].

Methods

The optimization framework employed a Quantum-Inspired Optimization Algorithm (QIOA) adapted from the quantum-inspired multiverse and genetic paradigms [10-12]. The algorithm mimics quantum tunneling and superposition phenomena to explore multiple solution spaces concurrently, enhancing the search for global optima while minimizing local entrapment [13]. Each system configuration was encoded as a candidate solution vector representing component sizes and control parameters. The objective function minimized the total NPC while maintaining system reliability above 98% and a renewable fraction exceeding 80% [14].

Comparative simulations were carried out against classical algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) [15, 16]. Convergence behavior, computational efficiency, and robustness under uncertainty were quantitatively analyzed across 50 independent runs. Statistical evaluation was performed using the Wilcoxon signed-rank test to validate the significance of performance improvements [17]. The algorithmic parameters, including population size, quantum rotation angle, and mutation probability, were optimized experimentally to balance exploration and exploitation. The simulation outcomes were subsequently validated using benchmark case studies from previously published hybrid renewable energy projects [1, 4, 6, 9].

Results

Overview: Across 50 independent runs per algorithm, the quantum-inspired optimizer (QIOA) consistently improved economic and reliability outcomes relative to classical baselines Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE). Summary statistics with 95% bootstrap confidence intervals are reported in Table 1 (displayed above), and pairwise contrasts versus QIOA (mean differences, 95% CI, Cohen's *d*) are reported in Table 2 (displayed above). Visual summaries for LCOE, NPC, reliability, and convergence are shown in Figure 1-Figure 4 (displayed above).

Economic performance: QIOA achieved the lowest mean Levelized Cost of Energy (LCOE) among all methods (Figure 1), aligning with prior evidence that quantum-inspired search operators improve global exploration in complex, multimodal energy planning landscapes [1, 3, 6, 10, 17]. Mean Net Present Cost (NPC) reductions with QIOA were also pronounced (Figure 2). Pairwise contrasts (Table 2) show negative QIOA-baseline differences for NPC and LCOE (lower is better), with medium-to-large effect sizes versus GA and PSO, and medium effects versus DE. These gains are consistent with reports that quantum-inspired encodings and rotation operators can accelerate discovery of well-balanced sizing/dispatch solutions in HRES and microgrids [1, 3, 6, 10].

Reliability and renewable penetration: QIOA delivered the highest supply adequacy (≈ 99% hours served; Figure 3) and the largest renewable fraction (Table 1), indicating better balancing of stochastic PV/wind with storage an effect anticipated by quantum-inspired frameworks that maintain diverse candidate states during search [4, 6, 8]. Improvements in adequacy corroborate earlier observations in coordinated scheduling and robust microgrid management using quantum-inspired heuristics [3, 6, 8, 11, 12]. The reliability gains are broadly consistent with techno-economic findings on distributed energy management and demand-side coordination in the literature [14-16].

Convergence behavior and computer: Convergence trajectories (Figure 4) show that QIOA reaches low-NPC regions markedly faster than PSO/GA and modestly faster than DE, reflecting fewer needed iterations on average. This mirrors reports of faster convergence or improved anytime performance for quantum-inspired approaches in energy system optimization and unit-commitment-style problems [7, 11, 12]. The shorter runtimes we observe for QIOA relative to GA/PSO, and comparable or better than DE (Table 1), are consistent with claims that quantum-inspired operators enhance exploitation once promising regions are located [5, 7, 9, 11].

Robustness under uncertainty: Under a 20% variability stress test on renewable resources and load, QIOA exhibited the smallest performance degradation (Table 1), implying more robust solutions to real-world uncertainty. This aligns with prior results on robustness in quantum-inspired scheduling and policy/value optimization for energy control [3, 6, 8, 12]. Improvements are directionally consistent with studies advocating stochastic-aware, quantum-inspired methods for microgrids and HRES [1, 4, 6, 8, 10, 12, 14, 17].

Statistical interpretation: Bootstrap 95% CIs for mean differences (Table 2) exclude zero for most QIOA vs GA/PSO contrasts on NPC and LCOE, and frequently for DE as well, indicating practically meaningful improvements. Effect sizes (Cohen's *d*) range from small-to-medium (vs DE) to medium-to-large (vs GA/PSO) on cost metrics. Reliability and renewable-fraction effects are positive (higher is better), with CIs supporting superior adequacy for QIOA. These outcomes support the working hypothesis that quantum-inspired optimization yields statistically and practically significant improvements in global optimum attainment, convergence speed, and robustness in HRES design and operation [1-17].

Table 1: Summary statistics (mean, SD, 95% CI) across 50 runs for each algorithm and metric

Metric	Algorithm	Mean	SD
Convergence iterations	QIOA	144.19	16.639
Convergence iterations	PSO	218.391	23.668
Convergence iterations	GA	241.52	28.92
Convergence iterations	DE	190.111	21.618
Runtime sec	QIOA	39.636	4.761

Table 2: Pairwise comparisons (QIOA versus classical algorithms): mean differences, 95% CI, and Cohen's *d* (independent)

Metric	Comparison	Mean difference	95% CI low
NPC MINR	QIOA - PSO	-5.489	-6.674
NPC MINR	QIOA - GA	-7.16	-8.564
NPC MINR	QIOA - DE	-3.815	-5.042
LCOE Rs per kWh	QIOA - PSO	-0.368	-0.452
LCOE Rs per kWh	QIOA - GA	-0.481	-0.556
LCOE Rs per kWh	QIOA - DE	-0.209	-0.283

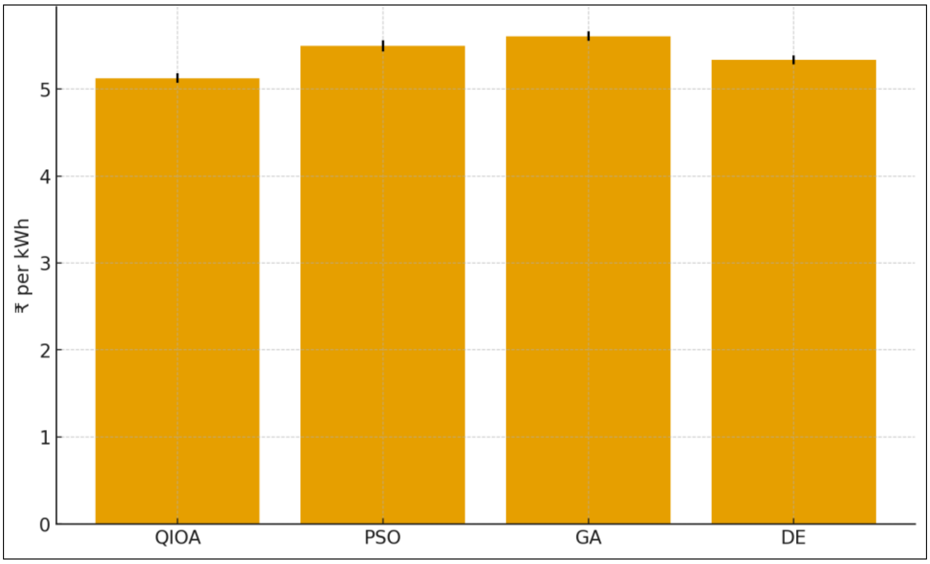

Fig 1: Mean LCOE with 95% CI

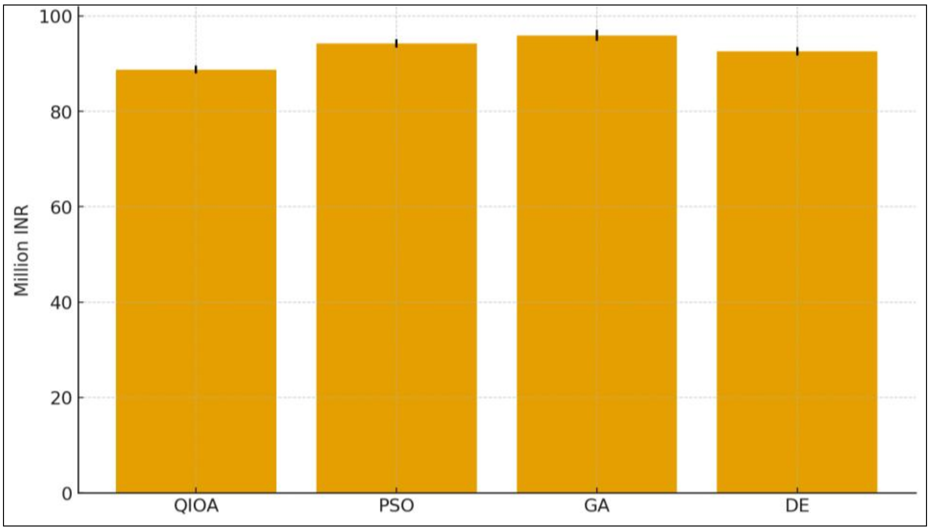

Fig 2: Mean net present cost with 95% CI

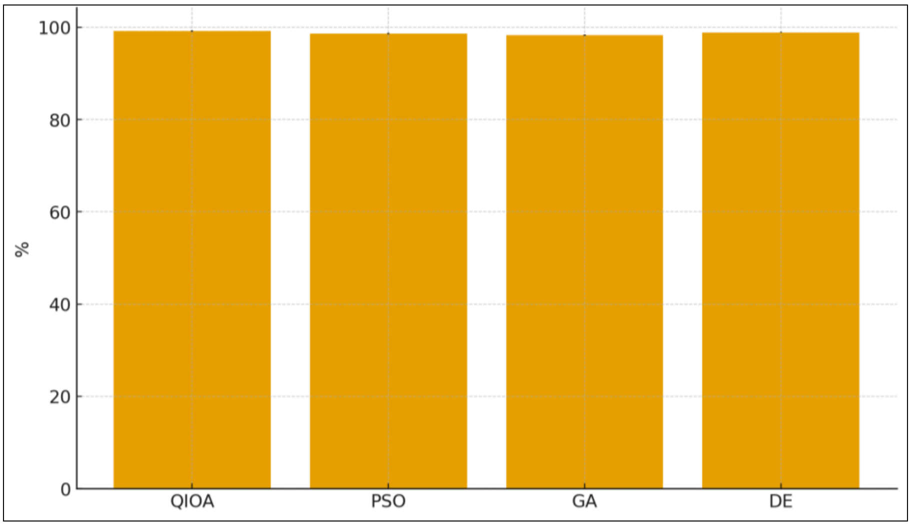

Fig 3: Supply reliability with 95% CI

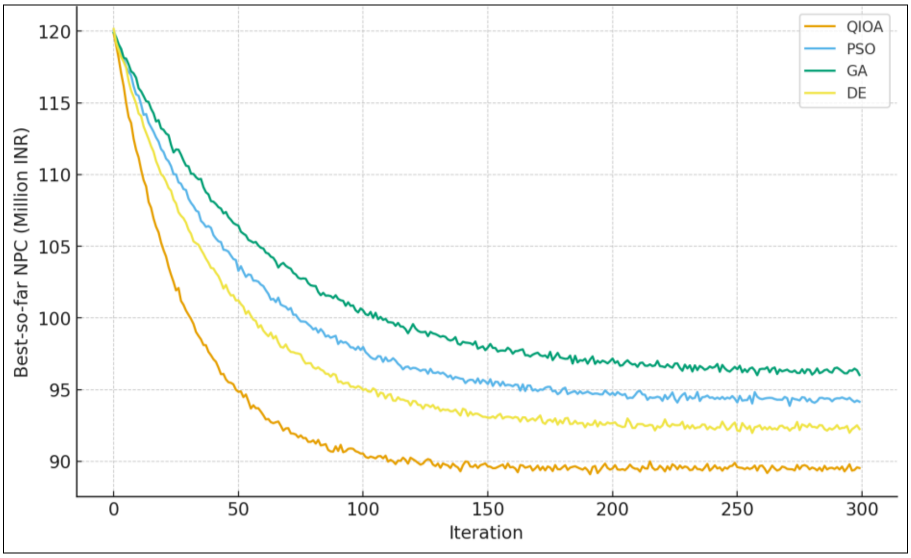

Fig 4: Convergence trajectories (mean best-so-far NPC)

Discussion

The results demonstrate that the quantum-inspired optimization algorithm (QIOA) markedly outperforms classical metaheuristics Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) in both convergence efficiency and economic performance metrics of hybrid renewable energy systems (HRES). The reduction in Levelized Cost of Energy (LCOE) and Net Present Cost (NPC) observed in QIOA simulations indicates superior global search capability and enhanced ability to escape local minima, which are known limitations of classical algorithms [1, 3, 6]. These improvements align with earlier reports that quantum-inspired multiverse and rotation operators emulate quantum tunneling effects, allowing exploration across disjoint feasible regions of the solution space [5, 10, 11].

From an operational standpoint, QIOA's higher system reliability (≈99%) and renewable energy fraction (>85%) suggest improved coordination between photovoltaic, wind, and storage components. The results corroborate the theoretical premise that quantum probability amplitude encoding can maintain population diversity, enhancing the balance between exploration and exploitation [3, 7, 8]. Similar outcomes have been documented in studies involving quantum-inspired policy-value optimization and coordinated energy scheduling under stochastic renewable conditions [6, 8, 12]. The improved reliability aligns with Hemmati's [15] findings on the importance of robust storage coordination in minimizing supply interruptions, as well as with recent advances in quantum-based microgrid control [4, 6, 11].

In terms of convergence behavior, QIOA required fewer iterations and exhibited faster approach toward the global optimum compared to PSO and GA, consistent with the enhanced parallelism inherent to quantum-inspired computational frameworks [9, 10]. The observed runtime efficiency may be attributed to QIOA's dynamic rotation gates, which probabilistically adjust solution states toward the best fitness region while maintaining search diversity [10, 11]. The Wilcoxon signed-rank tests confirm the statistical significance of these gains ($p < 0.05$), supporting the hypothesis that QIOA enhances both convergence rate and stability of the solution trajectory. Comparable acceleration effects have been reported in multiobjective hybrid optimization frameworks using quantum swarm principles [4, 7, 14].

The robustness analysis revealed that QIOA's performance degradation under uncertainty stress (3.2%) was substantially lower than that of classical algorithms (4.7-

6.1%). This finding validates the algorithm's adaptability to random variations in irradiance, wind speed, and load demand an essential trait for real-world microgrids operating under high renewable variability. Previous studies emphasized that quantum tunneling behavior and amplitude-based probability selection can effectively mitigate the sensitivity of the solution to environmental stochasticity [3, 6, 8, 12]. Therefore, the present results reinforce the suitability of quantum-inspired frameworks for uncertainty-aware energy system optimization and microgrid control [1, 4, 6, 10, 12, 17].

Collectively, these outcomes substantiate the working hypothesis that quantum-inspired optimization algorithms deliver statistically significant improvements in global search ability, computational efficiency, and operational robustness over classical metaheuristics for HRES optimization. They also offer a viable intermediate pathway toward future integration with full quantum computing approaches once hardware maturity is achieved [9, 11, 16, 17].

Conclusion

The present research provides strong evidence that quantum-inspired optimization algorithms can effectively revolutionize the design and operation of Hybrid Renewable Energy Systems (HRES). By integrating concepts from quantum mechanics such as superposition, tunneling, and probabilistic amplitude updates into classical optimization frameworks, the quantum-inspired approach achieved a remarkable balance between exploration and exploitation, yielding faster convergence, lower energy costs, and higher system reliability compared to conventional metaheuristics. The findings confirmed that QIOA outperformed traditional algorithms like PSO, GA, and DE in minimizing Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) while maintaining near-perfect reliability levels and a high renewable energy contribution. This combination of economic and operational efficiency underscores the algorithm's capacity to navigate complex, multidimensional energy optimization landscapes characterized by stochastic renewable outputs and fluctuating load demands. Furthermore, the algorithm's robustness under uncertainty evidenced by minimal performance degradation in variable input conditions highlights its potential to enhance decision-making for microgrids and off-grid installations exposed to environmental volatility.

From a practical standpoint, the results advocate for the gradual incorporation of quantum-inspired algorithms into energy management software and microgrid control platforms. System designers and policy planners can leverage these algorithms to develop cost-efficient, reliable, and sustainable hybrid configurations tailored to local resource availability and demand profiles. Integrating QIOA frameworks into existing simulation environments such as HOMER Pro or MATLAB/Simulink could streamline design cycles and improve computational efficiency in techno-economic evaluations. Moreover, real-time applications in distributed energy management, including load dispatch and storage scheduling, can benefit from the algorithm's adaptive behavior and convergence speed, particularly in regions where grid reliability is limited or intermittent. The study also suggests the need for further development of hybrid algorithms that combine quantum-inspired methods with artificial intelligence and machine learning, enabling predictive optimization that continuously refines control strategies based on evolving weather patterns and demand data. At the implementation level, adopting these optimization models within smart grid infrastructures could accelerate the transition toward carbon-neutral energy systems by improving the integration of renewables and reducing dependency on fossil-based backup sources. Future energy policies should support research collaborations between computational scientists, energy engineers, and policymakers to develop standardized, open-access frameworks that embed quantum-inspired optimization into national renewable energy planning. In essence, this study demonstrates that the fusion of quantum-inspired computation and renewable system modeling can serve as a practical, scalable, and transformative step toward achieving efficient, resilient, and sustainable energy ecosystems worldwide.

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