

Comparative Analysis of Classical and Quantum-Inspired Optimization for Net-Zero Emission Power Grid Operation

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Abstract: The transition toward net-zero-emission power grids has become increasingly challenging due to the growing penetration of renewable energy, the integration of energy storage, and the implementation of carbon-control policies. These developments increase the operational complexity of modern power systems and require optimization approaches capable of managing multiple technical and environmental constraints. **Objective:** This study aims to evaluate and compare the roles of classical optimization and quantum-inspired optimization in supporting the operation of low-carbon power grids under different energy-transition scenarios. **Method:** This research employed a quantitative approach using scenario-based modeling and simulation. The power-grid model integrated renewable energy sources, battery energy storage, and carbon-control mechanisms. Several transition scenarios were evaluated by varying renewable-energy targets, carbon prices, and emission caps. Comparative analysis was conducted using classical optimization based on Mixed-Integer Linear Programming (MILP) as the global optimum benchmark and quantum-inspired optimization based on simulated annealing as an alternative solution approach. **Findings:** The results show that classical optimization produces better solution quality and higher computational efficiency than the quantum-inspired approach. However, the quantum-inspired method is still able to generate feasible and stable solutions, particularly under scenarios with high renewable-energy penetration and strict emission constraints. **Implications:** These findings suggest that quantum-inspired optimization has practical potential as a complementary tool for supporting low-carbon power-grid operation and energy-transition planning, especially in increasingly complex systems. **Originality:** The novelty of this study lies in the direct comparison between classical and quantum-inspired optimization within a unified low-carbon power-grid simulation framework. The study provides added value by positioning quantum-inspired optimization as a complement, rather than a substitute, to classical optimization in net-zero-emission power-grid transition.

Keywords: Power Grid Optimization; Energy Transition; Renewable Energy; Quantum-Inspired Optimization

INTRODUCTION

The transition toward net-zero-emission power systems has become a strategic priority in both global energy policy and engineering research. The electricity sector remains one of the largest contributors to greenhouse-gas emissions, making deep decarbonization of power systems essential for achieving long-term climate targets. At the same time, the rapid

deployment of solar and wind generation, the electrification of transport and industry, and the growing use of battery energy storage are fundamentally changing the operational characteristics of modern grids. As explained by (Tian et al., 2023), clean energy plays a critical role in decarbonizing electricity generation and related sectors. Likewise, (Kabeyi & Olanrewaju, 2022) emphasize that low-carbon grid transformation is a necessary pathway toward sustainable electricity supply. In addition, (Hassan et al., 2023) note that the increasing dependence on renewable energy sources introduces technical and operational challenges due to intermittency and uncertainty. These developments make modern power systems more dynamic and computationally demanding than conventional fossil-dominated systems.

A first stream of literature focuses on renewable energy integration and low-carbon grid transition. In this stream, (Kabeyi & Olanrewaju, 2022) argue that the gradual replacement of fossil-based generation with renewable and low-carbon resources is central to the energy transition. Similarly, (Rahman et al., 2024) show that high renewable penetration significantly increases the need for flexibility in balancing generation, storage, and demand response. From a broader systems perspective, (Zhang et al., 2025) explain that achieving net-zero-carbon operation requires not only renewable integration but also energy-efficiency improvements and coordinated operational management. These studies collectively indicate that the transition to net-zero power systems is not merely a matter of adding renewable capacity, but also of improving how the grid is operated and optimized under increasingly complex conditions.

A second stream of literature addresses classical optimization and artificial-intelligence-based approaches for power-system operation. Classical optimization methods remain important because they provide reliable and structured solutions for dispatch, scheduling, and operational planning in power systems. At the same time, the use of artificial intelligence has expanded rapidly in renewable-energy optimization. For instance, (Ukoba et al., 2024) highlight that AI-based approaches can improve renewable energy system performance through better prediction, optimization, and operational control. In a related discussion, (Cholidis et al., 2025) show that integrated planning frameworks are increasingly required to coordinate storage, hybrid resources, and implementation pathways in low-carbon energy systems. However, as problem size, system uncertainty, and operational constraints increase, classical and AI-based approaches may still face

scalability and computational-efficiency limitations. This suggests that more advanced computational paradigms may be needed for future net-zero grid applications.

A third stream of literature examines quantum computing and quantum-inspired optimization for energy and power applications. (Ajagekar & You, 2019) introduced quantum computing as a promising tool for solving complex optimization problems in energy systems. In the context of smart grids, (Ullah et al., 2022) discuss the potential relevance of quantum computing for handling advanced operational problems. More specifically for power systems, (Golestan et al., 2023) provide an overview of recent advances in quantum computation and show that this field is gaining attention for energy-related applications. Furthermore, (Morstyn & Wang, 2024) identify significant opportunities for quantum computing in net-zero power systems, especially for large-scale optimization challenges. On the algorithmic side, (Hua et al., 2025) demonstrate the applicability of a quantum-inspired multi-objective optimization framework in an energy-related transportation setting, while (Munawar & Surendro, 2024) show that quantum-based approaches are increasingly being linked to carbon-neutrality problems. Nevertheless, most previous studies remain focused on conceptual reviews, algorithmic development, or limited case studies. Direct comparative studies between classical optimization and quantum-inspired approaches in the operational context of net-zero-emission power grids are still relatively limited. This gap is important because the practical usefulness of such methods can only be assessed under realistic renewable, storage, and emission constraints.

Based on this gap, the objective of this study is to evaluate and compare the performance of classical optimization and quantum-inspired optimization in supporting the operation of a power system transitioning toward net-zero emissions. To achieve this objective, a low-carbon power-grid model is developed by integrating renewable generation, conventional generation, battery energy storage, and carbon-control mechanisms such as carbon pricing and emission caps. The model is then tested under multiple transition scenarios representing different levels of renewable penetration, storage capacity, and emission restriction. System performance is assessed using indicators that are directly relevant to net-zero transition planning, including total operating cost, total carbon emissions, renewable energy utilization, renewable curtailment, and supply reliability.

This study is based on the argument that the increasing complexity of modern power systems driven by renewable intermittency, storage coordination, and carbon-constrained

operation requires optimization approaches that can explore large solution spaces more effectively. The working hypothesis is that classical deterministic optimization, such as Mixed-Integer Linear Programming, will continue to provide the best solution quality for well-structured system models, whereas quantum-inspired optimization can serve as a complementary approach capable of generating feasible and stable solutions under tighter constraints and greater combinatorial complexity. In this sense, quantum-inspired methods are not positioned as direct replacements for classical optimization, but rather as promising exploratory tools that may become increasingly valuable in hybrid optimization frameworks for future net-zero-emission power grids.

RESEARCH METHOD

The unit of analysis in this study is the operation of a low-carbon power grid system under net-zero emission transition scenarios. The system is modeled as an integrated electricity network consisting of renewable energy generation, conventional generation, battery energy storage, and carbon-control mechanisms. The analysis focuses on how different optimization approaches affect system performance in terms of operating cost, carbon emissions, renewable energy utilization, curtailment, and supply reliability. Therefore, the object of this research is not an individual or institution, but a simulated power-system model representing the operational behavior of an electricity grid undergoing energy transition.

This study employs a quantitative-exploratory research design using computational modeling and simulation. A quantitative design was selected because the research aims to evaluate measurable system-performance indicators under multiple energy-transition conditions. The exploratory nature of the study lies in its attempt to examine the potential role of quantum-inspired optimization compared with classical optimization approaches in supporting the operation of low-carbon electricity systems. Because the practical implementation of full quantum computing in real-world power systems is still limited by current hardware constraints in the Noisy Intermediate-Scale Quantum (NISQ) era, simulation-based analysis provides a realistic and controlled framework for evaluating optimization performance. The overall research workflow and methodological stages adopted in this study are illustrated in Figure 1.



Figure 1. Research workflow for evaluating classical and quantum-inspired optimization in net-zero power grid operation.

The study uses secondary and model-based data as its primary information sources. These include system load profiles, renewable generation characteristics, battery storage parameters, emission factors of conventional generators, and carbon-policy assumptions such as carbon prices and emission limits. The modeled system represents a simplified power grid operating over a 24-hour scheduling horizon with hourly resolution. Technical parameters including generator capacity limits, renewable availability, battery charging–discharging limits, and electricity demand levels are used as model inputs to represent the operational characteristics of a low-carbon electricity system under different transition conditions.

Data collection in this research was conducted through a model construction and parameter specification process. First, the structure of the power system was defined by identifying its main components, including renewable energy generators, conventional generators, battery energy storage, and demand profiles. Second, operational assumptions and transition parameters were determined, including renewable share targets, storage capacities, carbon pricing levels, and emission constraints. Third, the optimization problem was formulated by defining objective functions and system constraints such as power balance, generation limits, storage operation constraints, and emission control policies.

Two computational approaches were then implemented: a classical optimization method as the baseline and a quantum-inspired optimization approach to explore alternative solution behavior under identical system conditions.

The data analysis was performed using comparative computational analysis. Optimization results obtained from the classical and quantum-inspired approaches were evaluated using the same performance indicators, including total operating cost, total carbon emissions, renewable energy utilization, renewable curtailment, unserved energy, and computational runtime. The analysis proceeded through several stages. First, solution feasibility and stability were evaluated for each energy-transition scenario. Second, the numerical results from both optimization approaches were compared to identify differences in operational efficiency, emission reduction capability, and system reliability. Finally, the findings were interpreted to determine the conditions under which quantum-inspired optimization may provide advantages or limitations relative to classical methods in supporting the operation of net-zero-emission power systems.

RESULT

Classical Optimization Results for Net-Zero Emission Power Grid Operation

The simulation experiment in this study was designed to evaluate the performance of power-grid optimization in supporting the transition toward net-zero-emission conditions through a 24-hour operational scheduling horizon with hourly resolution. The power system was modeled as an integrated network consisting of renewable generation (solar and wind), gas-based generation as the carbon-emitting source, and battery energy storage. To represent different stages of energy transition, four experimental scenarios were defined: S1 (Baseline), S2 (Mid Transition), S3 (Advanced Transition), and S4 (Near Net-Zero Condition). In each scenario, the operational problem was formulated as a multi-objective optimization model that minimizes operating cost and carbon emissions while satisfying technical constraints, including power balance and capacity limits. Classical optimization based on Mixed-Integer Linear Programming (MILP) was used as the baseline approach.

Table 1. Classical Experimental Scenarios for Net-Zero Emission Power Grid Optimization

Scenario	Renewable Target	Share Battery (MWh)	Capacity	Carbon Price	Emission (tCO ₂)	Cap
S1_Baseline	0.2 (20%)	0		0	-	
S2_Mid	0.5 (50%)	50		50	-	
S3_High	0.8 (80%)	100		150	-	
S4_EmissionCap	0.8 (80%)	100		0	51.82	

Table 1 presents the baseline scenario configurations used in the classical optimization experiment. Each scenario represents a different stage of the energy transition, distinguished by renewable share targets, battery storage capacity, and carbon-control mechanisms. Scenario S1 represents the initial system condition with low renewable penetration and no carbon policy. Scenario S2 introduces a higher renewable target, battery integration, and a moderate carbon price. Scenario S3 represents a more advanced transition with dominant renewable penetration, larger battery storage, and a stronger carbon-pricing mechanism. Scenario S4 applies a strict emission cap to approximate near-net-zero operating conditions.

Based on these configurations, each scenario was simulated using the MILP model to obtain the optimal operating solution over the defined scheduling horizon. The resulting outputs provide a quantitative description of changes in operating cost, total carbon emissions, renewable-energy utilization, renewable curtailment, and supply reliability across the transition stages. The summary of the baseline classical optimization results is presented in Table 2.

Table 2. Summary of baseline classical optimization results for all energy transition scenarios

Scenario	Renewable Share Target	Battery Capacity (MWh)	Carbon Price	Emission (tCO ₂)	Cap Status	Total Cost	Total Emission (tCO ₂)	Unserved Energy (MWh)	Curtailment (MWh)	Renewable Used Share
S1_Baseline	0.2	0	0	-	Optimal	74,844.40	518.15	0.00	≈0	0.20
S2_Mid	0.5	50	50	-	Optimal	60,891.92	313.16	0.00	≈0	0.50
S3_High	0.8	100	150	-	Optimal	33,080.74	112.35	0.00	≈0	0.80
S4_EmissionCap	0.8	100	0	51.82	Optimal	411,046.59	51.82	134.52	≈0	0.80

Table 2 summarizes the results of classical optimization for all scenarios. All cases achieved optimal solution status, indicating that the model successfully produced feasible and stable operating decisions under the tested configurations. The numerical results show clear differences in cost, emissions, and reliability as the system transitions from low-renewable operation to more constrained low-carbon operation.

In S1 (Baseline), the system is still strongly dependent on gas-based generation, resulting in the highest carbon emissions among all scenarios. In S2 (Mid), increasing the renewable target to 50% and introducing 50 MWh of battery storage reduced both total cost and emissions while maintaining zero unserved energy. In S3 (High), the combination of 80% renewable penetration, larger storage capacity, and a high carbon price produced the lowest total operating cost and a substantial reduction in carbon emissions. In contrast, S4 (EmissionCap) achieved the lowest emissions due to the strict cap, but this result was accompanied by a very large increase in total cost and the appearance of significant unserved energy.

Dispatch Profile Analysis under Classical Optimization

Beyond aggregate indicators, the operational behavior of the system was also examined through dispatch-profile analysis. This analysis focuses on how different generation sources and battery storage contribute to meeting demand over time. To represent the advanced transition condition, the dispatch profile was evaluated for Scenario S3 (High Renewable Penetration), which provides the most balanced combination of renewable dominance, storage integration, and carbon pricing among all tested scenarios.

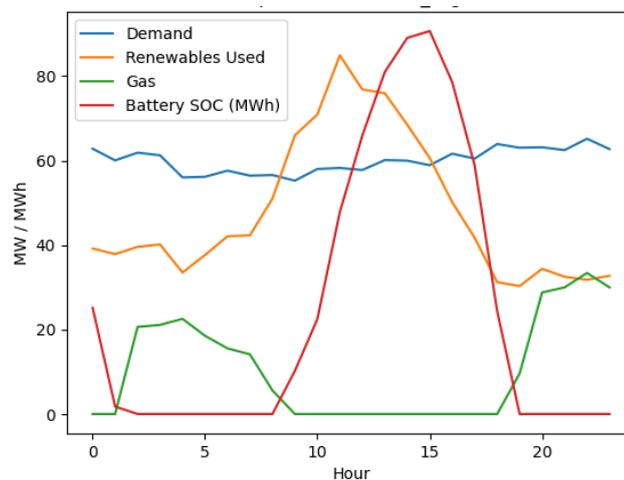


Figure 2. Dispatch Profile of the Power Grid under the S3 (High Renewable Penetration) Scenario

Figure 2 illustrates the hourly dispatch pattern of the power grid under Scenario S3 over the 24-hour scheduling horizon. The figure shows the contribution of renewable energy, gas-based generation, and battery state of charge (SOC) in maintaining the supply–demand balance. During daytime hours, when renewable availability is high, renewable generation becomes the dominant source of electricity supply. In this period, gas generation is reduced to nearly zero, indicating that the system prioritizes cleaner energy sources whenever available. Excess renewable energy is absorbed by the battery, as shown by the increase in SOC. During the evening and nighttime periods, when renewable generation decreases, the battery discharges to support the load, thereby reducing the dependence on gas generation. Under this operating pattern, gas generation serves mainly as a flexible backup source.

Quantum-Inspired Optimization Results for Net-Zero Power Grid Operation

After establishing the classical optimization baseline, the next stage of the study explored the potential of quantum-inspired optimization in supporting the operation of a low-carbon power grid. In this research, the quantum-inspired method was implemented using simulated annealing. This approach was applied to the same operational problem and under the same scenario structure as the classical model to ensure direct comparability. The evaluated indicators remained identical, including total operating cost, total emissions, renewable-energy utilization, renewable curtailment, supply reliability, and runtime.

Table 3. Quantum-Inspired Optimization Results Using Simulated Annealing

Scenario	Renewable Share Target	Battery Capacity (MWh)	Carbon Price	Emission Cap (tCO ₂)	Total Cost	Total Emission (tCO ₂)	Unserviced Energy (MWh)	Curtailment (MWh)	Renewable Share	Runtime (sec)
S1_Baseline	0.2	0	0	-	74,750.00	517.5	0.0	30.52	0.1788	4.78
S2_Mid	0.5	50	50	-	62,125.00	319.5	0.0	29.56	0.4795	4.17
S3_High	0.8	100	150	-	49,025.00	166.5	0.0	63.98	0.7555	4.01
S4_Emission Cap	0.8	100	0	51.82	457,150.00	49.5	150.0	18.26	0.7873	5.20

Table 3 shows that the quantum-inspired simulated annealing approach produced feasible solutions for all scenarios with short runtime values. In S1 (Baseline), the results are close to those of the classical optimization, although renewable curtailment appears and the renewable used share is slightly below the target. In S2 (Mid), the method maintains

zero unserved energy, but the total cost and emissions are slightly higher than those of the classical baseline. In S3 (High), the solution remains feasible and reliable in terms of supply adequacy, but total cost, total emissions, and renewable curtailment are notably higher than in the MILP result. In S4 (EmissionCap), the method keeps emissions close to the required limit, but this is achieved at the expense of extremely high cost and substantial unserved energy.

Dispatch Profile Analysis under Quantum-Inspired Optimization

To further evaluate the operational characteristics of the quantum-inspired method, the dispatch profile of Scenario S3 was analyzed. This scenario was selected because it represents a high-renewable and high-complexity condition without the extreme reliability loss observed in the emission-cap case.

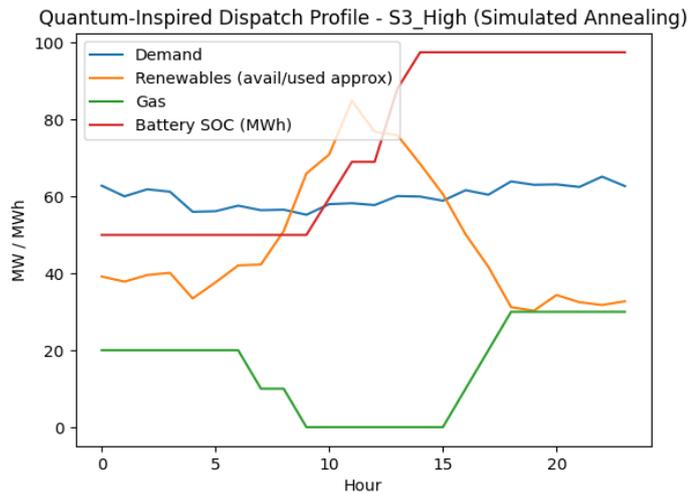


Figure 3. Quantum-Inspired Dispatch Profile under the S3 (High Renewable Penetration) Scenario

Figure 3 presents the dispatch profile obtained from the quantum-inspired simulated annealing approach under Scenario S3. Renewable generation remains the primary source of supply, particularly during periods of high availability. However, compared with the classical optimization result, the figure indicates a higher level of renewable curtailment and a less efficient use of available renewable energy. The battery charging and discharging pattern is also more aggressive, with SOC reaching high levels earlier and remaining elevated for longer periods. This operating behavior suggests that the heuristic search tends to preserve storage more conservatively while still attempting to reduce dependence on gas

generation. Gas generation continues to provide flexible support, especially during hours when renewable generation decreases.

Comparative Results between Classical and Quantum-Inspired Optimization

A direct comparison between the two optimization approaches reveals consistent differences in solution quality across all scenarios. In general, the classical MILP-based method produces lower operating cost, lower emissions, lower renewable curtailment, and better renewable-energy utilization than the quantum-inspired method. These differences become more pronounced as system complexity increases, particularly in Scenario S3 and Scenario S4.

The comparison is especially visible in renewable-energy performance. Under classical optimization, renewable curtailment remains nearly zero in all scenarios, whereas the quantum-inspired method shows measurable curtailment in every case. Likewise, the renewable used share under the classical approach matches the target value in each scenario, while the quantum-inspired approach remains slightly below the target. These differences are summarized visually in Figure 4.

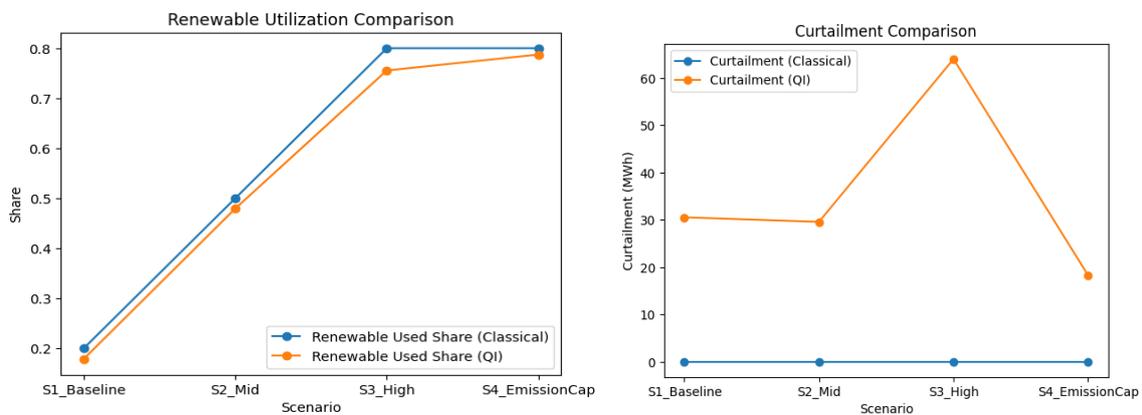


Figure 4. Comparison of Renewable Energy Curtailment between Classical and Quantum-Inspired Optimization (a, left) Renewable energy utilization (b,,right) Renewable energy curtailment

Figure 4 (a) shows that the classical optimization approach consistently achieves renewable utilization levels that are closer to the specified targets. Figure 4 (b) shows that renewable curtailment under the quantum-inspired method is consistently higher than under the classical method. These results confirm that the quality of renewable-energy coordination is one of the main distinguishing features between the two approaches.

DISCUSSION

This study evaluated the operational performance of a low-carbon power grid under four energy-transition scenarios by comparing classical optimization based on Mixed-Integer Linear Programming (MILP) and a quantum-inspired optimization approach using simulated annealing. The results indicate that increasing renewable-energy penetration, integrating battery energy storage, and applying carbon-control mechanisms significantly influence system operating cost, carbon emissions, renewable-energy utilization, and supply reliability. Among the evaluated scenarios, Scenario S3 characterized by high renewable penetration, battery storage integration, and carbon pricing provides the most balanced outcome in terms of low operating cost, substantial emission reduction, and full supply adequacy. In contrast, Scenario S4, which imposes a strict emission cap without carbon pricing, achieves the lowest emissions but results in a substantial increase in operating cost and unserved energy. The comparative results further show that the classical MILP approach consistently produces higher-quality solutions than the quantum-inspired approach, especially under highly constrained operating conditions.

The observed results can be explained by the interaction among renewable-energy penetration, storage flexibility, and carbon-control mechanisms in the operational model. The improvement from S1 to S3 occurs because higher renewable penetration reduces dependence on gas-based generation, while battery storage enables excess renewable energy to be shifted from high-generation periods to hours with lower renewable availability. In this way, storage improves temporal flexibility and helps maintain the supply–demand balance under variable renewable conditions. This finding is consistent with previous studies emphasizing that renewable expansion must be supported by flexibility resources and coordinated operational management to achieve effective low-carbon transition ([Hassan et al., 2023](#); [Rahman et al., 2024](#); [Zhang et al., 2025](#)).

The role of carbon pricing further explains the favorable performance observed in Scenario S3. Carbon pricing creates an economic signal that discourages carbon-intensive generation and incentivizes the use of renewable and low-carbon resources, thereby improving both environmental and economic performance ([Kabeyi & Olanrewaju, 2022](#)). By contrast, the strict emission-cap mechanism applied in Scenario S4 acts as a rigid operational constraint. Unlike carbon pricing, which still allows the model to balance cost and emissions flexibly, an emission cap forces the system to satisfy a fixed environmental threshold regardless of operational difficulty. Under the tested system conditions, this

reduces the feasible operating space and increases the likelihood of higher cost and supply inadequacy. This result supports the argument that the success of sustainable energy transition depends not only on environmental ambition, but also on the flexibility and readiness of system infrastructure and operation ([Hassan et al., 2023](#); [Saleh & Hassan, 2024](#)).

The difference between the classical and quantum-inspired optimization results can also be explained by their algorithmic characteristics. MILP solves the scheduling problem through deterministic mathematical programming and is well suited for structured optimization problems with clearly formulated constraints. In contrast, simulated annealing performs a heuristic and probabilistic exploration of the solution space. This characteristic allows it to generate feasible solutions relatively quickly, but it does not guarantee global optimality. As system complexity increases, this limitation becomes more visible through higher curtailment, higher cost, and lower renewable-utilization efficiency. This interpretation is consistent with the broader optimization literature, which shows that quantum and quantum-inspired approaches are promising for combinatorial and high-dimensional problems, but their practical performance still depends strongly on formulation quality, search strategy, and problem structure ([Kurowski et al., 2023](#); [Raseena, 2025](#)).

The findings of this study are in line with previous research on renewable-energy integration and low-carbon grid operation. Earlier studies have shown that high renewable-energy penetration alone does not automatically result in efficient decarbonization unless the system is supported by adequate flexibility mechanisms such as storage, hybrid coordination, and adaptive operational planning ([Cholidis et al., 2025](#); [Hassan et al., 2023](#); [Rahman et al., 2024](#)). The present results reinforce this view by demonstrating that the combination of renewable generation, battery storage, and carbon pricing yields significant reductions in both cost and emissions while maintaining reliability.

The results also support previous studies that highlight the importance of policy design in energy transition. ([Kabeyi & Olanrewaju, 2022](#)) emphasize that low-carbon electricity transition requires not only renewable deployment but also appropriate policy frameworks. In the present study, the carbon-pricing scenarios perform better than the strict emission-cap scenario in maintaining a balance between decarbonization and operational feasibility. This suggests that market-based emission-control mechanisms may provide a more flexible and practical transition pathway than rigid constraints under certain system conditions.

With respect to computational approaches, the results are consistent with recent studies describing the growing relevance of quantum computing and quantum-inspired methods in energy-system applications ([Munawar & Surendro, 2024](#); [Ullah et al., 2022](#)). Recent literature also suggests that quantum-based and quantum-inspired techniques may become increasingly useful for addressing complex optimization problems in sustainability, energy management, and engineering systems ([Gill & Buyya, 2026](#); [Jami & Haleem, 2025](#); [Tangpanitanon, 2025](#)). However, many of these studies remain conceptual, review-based, or focused on algorithmic development rather than direct benchmarking against established classical methods. Therefore, the novelty of this study lies in its direct comparison between classical and quantum-inspired optimization within the same low-carbon power-grid simulation framework, using identical transition scenarios and evaluation indicators. In this sense, the study contributes empirical evidence to a research area that is still largely exploratory.

The results provide several broader implications for understanding the transition toward net-zero-emission power systems. First, they show that decarbonization is not merely a matter of increasing renewable installed capacity. Rather, it is an operational coordination problem involving the interaction among variable renewable generation, storage dynamics, backup generation, and carbon-policy instruments. This means that achieving net-zero operation requires not only technological substitution, but also a more sophisticated framework for managing system flexibility and operational trade-offs. Such an interpretation is consistent with the view that clean-energy transition is a systemic transformation rather than a single-technology intervention ([Saleh & Hassan, 2024](#); [Tian et al., 2023](#)). Second, the results indicate that optimization methodology itself shapes how the transition is understood. Classical optimization and quantum-inspired optimization do not merely produce different numerical results; they also reflect different capacities for exploring and prioritizing system trade-offs. This means that computational tools are not neutral instruments in energy planning. Instead, they influence how feasibility, efficiency, and sustainability are interpreted in the design of future energy systems.

Third, the study suggests that quantum-inspired optimization should currently be interpreted as an exploratory and complementary approach rather than as a substitute for classical optimization. Although the simulated annealing method does not outperform MILP in this study, it still demonstrates the ability to produce feasible and stable solutions across all scenarios. This indicates that quantum-inspired methods may become

increasingly relevant as future energy systems grow in scale, dimensionality, and constraint complexity, especially when integrated within broader hybrid decision-support frameworks (Gill & Buyya, 2026; Tangpanitanon, 2025; Ullah et al., 2022).

The findings reveal both functional and dysfunctional aspects of the transition toward net-zero-emission power grids. On the functional side, the results show that renewable-energy expansion, when combined with battery storage and an appropriate carbon-pricing mechanism, can reduce both emissions and operating cost without compromising system reliability. This demonstrates that environmental sustainability and economic efficiency can be mutually reinforcing when supported by adequate operational flexibility and well-designed policy instruments.

On the dysfunctional side, the results also show that an overly rigid emission-control strategy can generate unintended negative consequences. In Scenario S4, the strict emission cap successfully reduces emissions, but it also leads to very high operating costs and significant unserved energy. This suggests that aggressive environmental constraints, when applied without sufficient technical flexibility, may undermine the operational reliability of the system. The same reflection applies to the use of emerging optimization methods. Although the quantum-inspired approach offers promising exploratory capability, its current limitations in renewable coordination and solution quality indicate that premature reliance on such methods without hybrid enhancement may produce suboptimal operational outcomes. These findings reinforce the view that sustainable transition should be managed through balanced coordination among environmental targets, economic feasibility, computational capability, and system reliability.

Based on the findings, several practical implications can be proposed. First, policymakers and system planners should prioritize battery energy storage as a core component of net-zero power-grid transition. Storage is essential not only for absorbing excess renewable generation, but also for reducing curtailment, improving flexibility, and maintaining supply adequacy under variable renewable conditions.

Second, emission-control policies should be designed in a flexible and adaptive manner. The results suggest that carbon pricing provides a more balanced pathway for reducing emissions than a rigid emission cap, especially during intermediate and advanced transition stages. Therefore, policymakers should consider gradual and market-responsive carbon policies before imposing strict caps that may exceed the current flexibility of the system.

Third, future power-system planning should explicitly consider computational strategy as part of transition planning. Since different optimization approaches produce different operational patterns and trade-offs, selecting an appropriate optimization framework is important for obtaining reliable and policy-relevant planning results. In this context, classical optimization remains the most reliable method for structured grid-operation problems, while quantum-inspired optimization may serve as a complementary tool for exploring increasingly complex solution spaces.

Finally, future research and development should focus on hybrid optimization architectures that combine the deterministic strength of classical methods with the exploratory capacity of quantum-inspired approaches. Such hybrid frameworks may offer better scalability for large and complex low-carbon energy systems, while preserving acceptable solution quality. In this way, the transition toward net-zero-emission power grids can be supported not only by renewable technologies and carbon policies, but also by advances in computational intelligence and optimization design.

CONCLUSION

This study demonstrates that the transition toward a net-zero-emission power grid is strongly influenced by the coordinated interaction among renewable-energy penetration, battery energy storage, and carbon-control mechanisms, as well as by the optimization method used to manage system operation. The main finding of this research is that classical optimization based on Mixed-Integer Linear Programming (MILP) provides the best overall performance for the tested system, as it is able to significantly reduce carbon emissions and operating costs while maintaining supply reliability under high-renewable scenarios. In particular, the results show that a transition pathway combining high renewable penetration, battery storage, and carbon pricing produces the most balanced outcome in terms of economic efficiency, environmental performance, and operational stability. At the same time, the study also finds that quantum-inspired optimization based on simulated annealing is capable of generating operationally feasible solutions across all transition scenarios, including cases with high renewable penetration and strict emission constraints, although its solution quality does not yet consistently exceed that of the classical approach.

The main scientific contribution of this study lies in its direct comparative evaluation of classical and quantum-inspired optimization within a unified net-zero power-grid

framework. By integrating renewable-energy targets, battery storage, carbon pricing, and emission caps into the same operational simulation environment, this research provides a structured benchmarking perspective on how different optimization paradigms perform under low-carbon transition conditions. The study contributes not only empirical results on cost, emissions, renewable utilization, curtailment, reliability, and runtime, but also a broader conceptual insight that quantum-inspired optimization should presently be viewed as a complementary tool rather than a replacement for classical optimization. In this sense, the research adds value by positioning quantum-inspired methods as promising exploratory approaches for complex and high-dimensional energy-system problems, while reaffirming the continuing strength of MILP for structured operational planning. The findings also open a pathway for future hybrid classical–quantum optimization frameworks in net-zero power-system planning.

This study has several limitations that should be acknowledged. First, the analysis is based on a simplified 24-hour power-grid model with hourly resolution and does not yet represent the full spatial, temporal, and network complexity of real-world electricity systems. Second, the quantum-inspired approach examined in this study is limited to simulated annealing, and therefore does not represent the full range of possible quantum-inspired or quantum-variational methods. Third, the model does not explicitly incorporate stochastic uncertainty in renewable generation, electricity demand, or real-time operational disturbances, which are important features of actual low-carbon grid operation. Because of these limitations, the results should be interpreted as an initial benchmarking study rather than a full real-system deployment analysis. Future research is therefore recommended to investigate hybrid optimization architectures, expand the study to larger and more complex network models, incorporate uncertainty and real-time operational data, and explore adaptive approaches supported by machine learning for dynamic decision-making in net-zero-emission power systems.

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