Quantum Optimization for Energy-Efficient Route-Finding

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The exponential growth in data center energy demand poses a challenge to the sustainability of future computation. According to the IEA, data centers may consume up to 8% of global electricity by 2030 [3, 4]. Among the most energy-intensive workloads are complex optimization problems like the Traveling Salesman Problem (TSP), which underlies logistics applications including routing for UPS and Amazon [5]. Certain quantum algorithms offer an alternative with potential reductions in both time and energy complexity.

To assess possible solutions, this work compares three algorithms for solving the Traveling Salesman Problem, which asks for the shortest possible route that visits each city exactly once and returns to the starting point. The brute-force method [6, 7] represents the most straightforward approach, checking every possible route to guarantee the best answer. The Held–Karp algorithm [6, 7] improves efficiency by reusing partial results through dynamic programming. Finally, the Quantum Approximate Optimization Algorithm (QAOA) [1] takes a different path: it encodes the problem into a quantum system, allowing it to explore many solutions simultaneously and converge on high-quality routes. To compare these methods fairly, we estimated the energy use of the classical algorithms based on how their computation grows with problem size. The energy use of the quantum algorithms was estimated based on the power consumption of IBM's Sherbrooke quantum computer [2], scaled according to gate execution time and assuming future hardware with a sufficient number of error-corrected qubits. Since current quantum systems do not yet provide the required scale of error-corrected qubits for these algorithms, this represents an idealized scenario. However, ongoing advances in quantum processors are expected to make such hardware increasingly feasible [8].

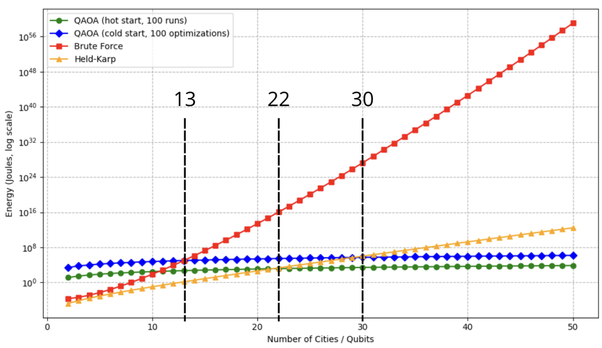

Figure 1: Energy use of classical vs. quantum algorithms

The comparison in Figure 1 highlights a clear distinction between classical and quantum approaches. As shown in the figure, the brute-force method quickly becomes impractical, with its energy use skyrocketing factorially and surpassing all other methods even at modest problem sizes. The Held–Karp algorithm provides an improvement, growing only exponentially, but still shows a steep upward trend and eventually becomes unsustainable as the number of cities increases. In contrast, the Quantum Approximate Optimization Algorithm (QAOA), both in its hot-start and cold-start variants[1], displays an almost flat energy profile in our models, suggesting that its scaling is far more favorable for large problem sizes. The vertical lines in the figure mark critical crossover points. At around 13 cities, QAOA with a cold start already consumes less energy than the brute force method. By 22 cities, the hot-started QAOA outperforms both brute force and Held–Karp and at 30 cities, the classical methods are no longer competitive at all.

These results carry significant sustainability implications. As data centers continue to expand and optimization tasks grow in scale, the steep energy demands of non-quantum algorithms pose a clear environmental challenge. In contrast, the modeled energy profile of QAOA points to a future where large-scale computations could be carried out with dramatically lower energy costs. This positions quantum optimization as more than a technical improvement, it is a potential enabler of sustainable digital infrastructure. By reducing the energy footprint of tasks central to logistics, urban planning, and large-scale computation, quantum algorithms align directly with the United Nations Sustainable Development Goals. Advancing SDG 9 (Industry, Innovation, and Infrastructure) through energy-efficient innovation, SDG 11 (Sustainable Cities and Communities) via sustainably scalable logistics and transport systems, and SDG 12 (Responsible Consumption and Production) by lowering emissions linked to computation [9].

It is important to note, that these results are based on theoretical models using idealized assumptions and cannot yet be achieved on today's error-prone, small-scale quantum processors. Instead, they point to the long-term potential of quantum computing to deliver substantial energy savings once hardware reaches the required scale and fidelity.

[1] In QAOA, a cold start sets parameters randomly and may need many iterations to converge. A hot start uses informed values, leading to faster convergence and better solutions.

References

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