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Exploring the Role of Quantum Computing in Advancing Green Computing Technologies

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Abstract

The rapid growth of data-intensive applications and cloud computing has significantly increased the energy consumption of modern computing infrastructures, particularly data centers, raising critical sustainability and environmental concerns. Green computing seeks to address these challenges by improving energy efficiency and reducing carbon footprints without sacrificing performance. Quantum computing has emerged as a promising paradigm due to its ability to exploit quantum mechanical principles such as superposition and entanglement to achieve computational speedups beyond classical limits. This paper examines the role of quantum computing in advancing green computing technologies by analyzing its algorithmic capabilities, application domains, and hardware-related energy implications. Key quantum algorithms, including Shor's algorithm, Grover's search, the Quantum Approximate Optimization Algorithm (QAOA), and quantum simulation methods, are reviewed with respect to their potential to reduce execution time and energy consumption for computationally intensive tasks such as cryptography, optimization, and system modeling. The study further explores sustainability-oriented applications, including energy systems optimization, materials discovery for renewable technologies, and quantum machine learning for resource forecasting and management. Comparative analysis indicates that quantum approaches may offer substantial energy-efficiency advantages over classical methods as hardware matures. However, significant challenges remain, including qubit decoherence, error correction overhead, cryogenic cooling requirements, and scalability limitations. The paper concludes that continued advances in hybrid quantum–classical architectures and fault-tolerant hardware are essential for realizing quantum computing's potential contribution to sustainable and energy-efficient computing.

Keywords: Electrical Engineering, Energy Efficiency, Green Computing, Quantum Computing, Sustainability

1. Introduction

As the global demand for computational power continues to rise, the energy consumption of computing systems has become a pressing issue. Data centers, which are central to cloud computing and large-scale data processing, now account for nearly 1% of global electricity consumption. this is expected to increase as demand grows (Katal et al., 2022). This significant rise in energy usage presents an urgent challenge, especially as the environmental impact of high energy consumption becomes an increasingly critical concern (Farghali et al., 2023). In response to this, green computing has gained considerable importance, focusing on strategies to minimize energy consumption, enhance hardware efficiency, and reduce the carbon footprint of computing systems, all without sacrificing performance (Bharany et al., 2022). Recent work has also explored data-efficient and energy-conscious system designs, such as improved primary indexing methods for large-scale databases (AlKhaldy et al., 2025).

Quantum computing is a new technology which is expected to solve these problems. The technology uses some principles of quantum mechanics, notably superposition and entanglement, in order to process information in a different way than classical computers (Rietsche et al., 2022). In classical computers, bits encode information in one of many possible states (0 or 1); quantum computers use qubits (quantum bits) that can be in many states simultaneously. Because of the ability for parallel computation, quantum computers can reduce the time complexity of certain problems exponentially, allowing for reduced computational time and potentially significant energy savings for some applications (Meglio et al., 2024).

Figure 1 demonstrates the most important difference: classical bits exist in a state of either 0 or 1, while quantum bits exist in a superposition of 0 and 1. This unique aspect of qubits allows quantum computers to perform the same computations in parallel, most likely saving time and energy used to solve complex problems.

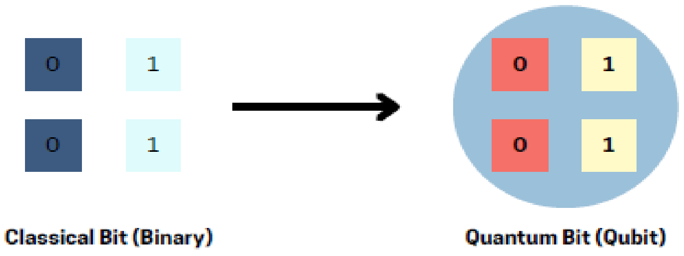

Figure 1: *Classical Bits vs Quantum Bits (Qubits) with Superposition.*

The ability of quantum computing to compute in parallel brings some interesting features of energy efficiency in areas of computation that are energy-intensive, such as optimization, cryptography, and simulations (Samunnisa et al., 2024). Quantum algorithms yield some benefit above and beyond classical algorithms via the principles of quantum mechanics. The results of quantum algorithms provide explicit improvement (Ge et al., 2022). Shor's algorithm for factoring large prime numbers (Cai, 2024), and Grover's algorithm that traverses an unordered database (Tonchev & Danev, 2024) are two examples of quantum algorithms that will be primarily efficient which relates to less energy expended in performing those operations. However, despite the promise of quantum computing, it is still significantly away from ease of use (Memon et al., 2024).

As a developing area of research, the field of quantum computing has many barriers to cross concerning hardware needing to scale with maintained qubit coherence and maintaining periodicity under cryogenic levels (de Leon et al., 2021).

Despite this, quantum computing is still an applicable platform for green computing and may be able to change how certain energy-consuming problems can be solved (Balicki, 2022). The purpose of this paper is to focus on quantum computing as a contributor to the development of green computing. By discussing how quantum algorithms may provide energy-efficient alternatives to classical computing and evaluating the current limitations associated with quantum hardware, this paper hopes to illustrate how quantum computing can contribute to more energy-efficient and eco-friendly computing. Ultimately, the aim is to demonstrate that quantum computing could fundamentally change the energy landscape of computational technologies while also supporting and advancing the mass transitions required by society for their growing demand for sustainability.

2. Background and Related Work

Quantum computing shifts the foundations of computation. While classical bits are defined as a discrete state of being either 0 or 1, quantum bits (or qubits) can be in a superposition of states, allowing specific types of problems to be solved with a vast degree of parallelism (Khan et al., 2024; Nimbe et al., 2021). Furthermore, CA entanglement allows qubits to remain correlated, regardless of their distance apart, and can allow for more complicated operations on multiple qubits and a speedup beyond classical limitations (Anders et al., 2023; Gill et al., 2021; Khrennikov, 2021). These capabilities allow very famous quantum algorithms such as Shor’s integer factorization algorithm and Grover’s database searching algorithm to execute with much less computation resources than any classical algorithm would. Figure 2 illustrates these key principles of superposition and entanglement.

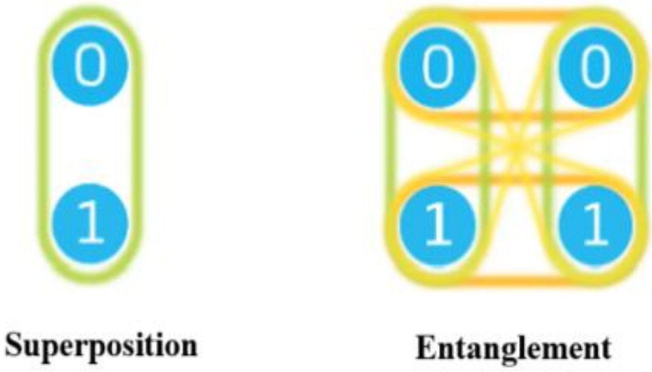

Figure 2: Superposition and Entanglement

Even with this potential, current quantum computers are still stuck in the Noisy Intermediate-Scale Quantum (NISQ) era: the devices utilize tens to hundreds of noisy qubits and cryogenic entanglement (Chakraborty & Joshi, 2024; Khan et al., 2024). Hybrid methods like the Variational Quantum Eigensolver (VQE) and Quantum Approximate Optimization Algorithm (QAOA) use quantum circuits with classical optimizers, thus respecting limits of hardware, but development of large-scale, fault-tolerant infrastructures is still limited based on decoherence, noise, and cryogenic requirements.

In addition to hardware advancements, there is a developing body of literature on how quantum computing may enable green and energy-efficient computing. Sood and Chauhan (2024) summarize the new emerging sustainable quantum computing field focused on energy and life cycle impacts. Work from Morstyn and Wang (2024), reviews quantum methods for optimizing net-zero power systems and combinatorial scheduling. Liu and Tang (2023) Provide a tutorial on quantum convex and machine-learning techniques for power systems. A Pacific Northwest National Laboratory (PNNL) report also describes architectural and benchmarking gaps for quantum-enhanced energy optimization (Asfaw et al., 2022). The most recent work from Amani and Kargarian (2025) proposed a coherent variational approach for Optimal Power Flow (OPF) using hybrid quantum algorithms. Together, these papers illustrate burgeoning but disparate work at the intersection of quantum computing and sustainability, thus motivating the synthesized and challenge analysis in this paper.

3. Methodology

This study examines the potential for quantum computing to enable green and energy-efficient workloads using a hybrid algorithm and hardware analysis approach. The analysis took place in three phases.

The first step was identifying quantum algorithms that they are known to offer an improvement in terms of computational speed, and are likely to also reduce execution time, and therefore indirectly lower energy consumption, as compared to classical implementations. Shor’s integer factorization algorithm (Cai, 2024), Grover’s unstructured database search (Tonchev & Danev, 2024), Quantum Approximate Optimization Algorithm (QAOA) (Kurowski et al., 2023), and quantum simulation potential (Xu et al., 2025), were selected in this analysis. These resources were most relevant based on the energy-intensive workloads such as combinatorial optimization, cryptography, and modeling complex systems.

The application areas for quantum computing suggested for sustainability were also examined. We predominantly focused on studies of energy systems optimization, materials discovery for renewable energy and energy storage, and quantum machine learning (QML) for resource management and forecasting. We focused on more recent literature from 2020 onwards, especially those that presented a decrease in the computational complexity, potential reduction in energy use, or performance evaluation. We also considered hybrid quantum–classical approaches since that is the current state of play in the Noisy Intermediate–Scale Quantum (NISQ) era.

In conclusion, we discussed hardware traits that dictate energy efficiency, namely qubit decoherence, quantum error correction overhead, cryogenic operation for superconducting systems, and scaling limits for other qubit platforms such as trapped-ion, topological, photonic, and silicon devices (Asfaw et al., 2022; Chakraborty & Joshi, 2024; Gill et al., 2021; Khan et al., 2024; Liu & Tang, 2023; Morstyn & Wang, 2024; Sood & Chauhan, 2024). We reviewed vendor roadmaps and recent reviews on low-power scalable quantum systems development.

The final synthesized connection relates the algorithmic potential in hardware to realistic hardware limitations and provides examples of energy consumption comparisons in Figure 3 and efficiency indicators in Table 1. This didactic connection serves as the foundation for the Results and Discussion sections that examine the real-world considerations of quantum speedups and hardware progress for sustainable computing.

4. Results and Discussion

Quantum computing has the potential to show energy efficiency advantages over classical systems for workloads. When a qubit is in computation mode, superposition and entanglement enable the qubits to simultaneously explore states of its many possible solutions in parallel instead of in serial execution, which reduces execution time and, in theory, total power draw for some types of problems (Jaschke & Montangero, 2023). This benefit can be important because a lot of problems do not fare well in classical systems, such as integer factorization, unstructured search like Grover's Search, and large combinatorial optimizations and reasoning.

Figure 3 presents a comparison of estimated energy consumption for classical and quantum systems in cases of optimization, cryptography, and simulation workloads. The data suggest that to easily reach a solution for these workload types, quantum systems will potentially require an order of magnitude less energy once stable quantum hardware becomes available.

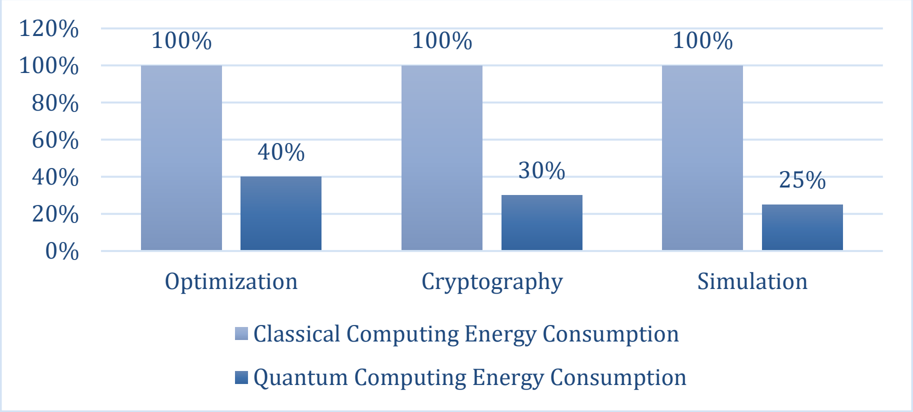

Figure 3: Energy Consumption Comparison Between Classical and Quantum Computing for Different Tasks

Table 1 shows the energy efficiency benefits of the various quantum algorithms against classical algorithms. As it showed, quantum algorithms, like Shor's Algorithm to factor large numbers, or Grover's Algorithm to search a database, have huge energy savings by completing the operation with greater efficiency and faster, using less energy. It also discussed how the quantum algorithms could promote sustainability in computations in the capture of theoretical energy savings in the areas of cryptography, optimization, and simulations.

Table 1: **Comparison of Quantum algorithms and their energy efficiency benefits**

Quantum Algorithm	Classical Equivalent	Energy Efficiency Benefit	Potential Application
Shor's Algorithm (Cai, 2024)	Classical integer factorization	Exponential factoring speedup reduces energy	Cryptography, security applications
Grover's Algorithm (Tonchev & Danev, 2024)	Unsorted database search	Quadratic search speedup lowers energy	Database search, AI, machine learning
Quantum Approximate Optimization Algorithm (Kurowski et al., 2023)	Classical optimization algorithms	Exponential optimization speedup cuts energy	Scheduling, routing, finance optimization
Quantum Simulation (Xu et al., 2025)	Classical simulations of quantum systems	Polynomial–exponential simulation reduces energy	Drug discovery, materials science

These comparisons are summarized in Table 1, which highlights the potential energy-efficiency benefits of these algorithms relative to their classical counterparts. Alternative strategies to enhance energy efficiency in current computing frameworks is the use of metaheuristic optimization-based methods for the Internet of Things (IoT), which include Whale Optimization with Simulated Annealing approach (Shaheen et al., 2025). These are in addition to quantum approaches and show the range of methods designed to minimize the energy required for computation.

Many algorithms that we have identified show possible savings:

- Shor's algorithm can factor supply customers exponentially faster than the time needed for existing classical methods, and it can save time and energy in processing cryptographic workloads (Cai, 2024).
- Grover's algorithm has a quadratic advantage for unstructured search, which can save database queries and expense (Tonchev & Danev, 2024).
- The Quantum Approximate Optimization Algorithm (QAOA) targets difficult combinatorial optimization problems and has been proposed for scheduling, routing, and financial portfolio optimization with lower computational overhead (Kurowski et al., 2023).
- Quantum simulation methods can simulate complex quantum systems at a higher efficiency than simulation with classical methods, resulting in application efficiency in material science and drug discovery (Xu et al., 2025).

4.1. Domain Applications Relevant to Green Computing

Apart from the algorithms alone, various application domains illustrate the potential of quantum methods for sustainability computing:

- Energy systems optimization: Conventional optimization of power systems, renewables scheduling, and electric vehicle charging networks is compute-intensive. QAOA and others' variational approaches can prune the search space and speed up the solution, reducing both run-time and operational energy use.
- Materials discovery: Quantum simulation can provide the capabilities to successfully simulate materials down to the electronic scale, and will subsequently be used to achieve more advanced and efficient photovoltaic cells, battery chemistries and carbon capture catalysts, which may further improve the energy storage and conversions technologies that support green infrastructure
- Quantum machine learning (QML): Hybrid quantum-classical learning methods can utilize applied Q-learning-type approaches that can excel at forecasting (e.g., wind or solar output) and predicting factors like supply chain or agricultural resource allocation, which can lead to efficiency in the delivery of energy to minimize waste
- Hybrid quantum-classical systems: In the foreseeable future, NISQ-era devices may build a layer of classical processors, sending the most difficult sub problems to quantum hardware, but relying on well-developed classical infrastructure for stability and scalability.

4.2. Hardware Efficiency Implication

Hardware advances are crucial to these potential energy savings. Some quantum gates can enact some transformations orders of magnitude faster than a big classical logic circuit would. The downside is reliance on extreme refrigeration and error correction overhead. This is the current state of systems (Chakraborty & Joshi, 2024; Khan et al., 2024). The potential for energy savings will only become more important with more elaborate devices that derive improvements from new materials, longer coherent time, and low-power controlled electronics. A fault-tolerant architecture to reduce the prevailing large error correction overhead will be critical in achieving energy savings at scale (Gonzalez-Zalba et al., 2021).

These findings imply that quantum algorithms might, in principle, provide computational energy savings on classes of difficult problems, while applications, such as optimizing power grids, developing materials, and quantum machine learning, may provide tangible benefits to green technology. Ultimately, the sustainability benefit would depend on hardware that operates efficiently and does not use wasteful cooling or additional resource extraction, which we address later under challenges.

5. Challenges in Scaling Quantum Computing

While quantum computing offers enormous computational and energy efficiencies, today's devices are still far from ready to fully deploy at scale and in practice. And one of the biggest barriers is quantum decoherence – loss of quantum information due to environmental noise or unwanted interactions. Decoherence destroys the delicate superposition and entanglement that are essential for computation and creates gate errors and limits the quantum circuit depth (Gill et al., 2021). Quantum error correction (QEC) is a theoretical approach to reliability, but it requires thousands of physical qubits to create a logical qubit, and requires complex real-time control which today's quantum hard-ware is unable to do (Sivak et al., 2023).

Additionally, the need for cryogenic operation is a hurdle: several of the best plat-forms, such as superconducting qubits, need to be chilled in millikelvin temperatures to maintain coherence and decrease error rate (Chakraborty & Joshi, 2024). These refrigeration units are elaborate and require power, which could offset some of the sustainability advantages of quantum computers.

There are a variety of qubit technologies being researched and developed to ad-dress these challenges, each presenting pros and cons in terms of scalability, stability and energy efficiency. Superconducting qubits allow for fast gates and are relatively advanced, but, depend on ultra-deep cryogenic refrigeration. Trapped ions can have very long coherence but pose challenges in scaling due to laser control and the ability to move ions accurately. Topologically protected qubits offer built-in error tolerance, but are still very much experimental at this point in time. Photonic qubits could offer entangled quantum links over longer distances of separation, but problems like lack of a photon and entanglement are still hurdles. Silicon qubits can potentially be made using conventional semiconductor fabrication process, but they continue to have challenges with electron control and uniformity of devices (Anferov et al., 2024; Gonzalez-Zalba et al., 2021).

Table 2 summarizes the results of the analysis. New material science, fault-tolerant architectures, and low-power control electronics are required in order to reduce error correction and cooling overheads in order to maximize quantum hardware efficiency and scalability. These advancements are the only viable means by which quantum computing would eventually realize its potential as a sustainable, energy-efficient technology.

***Table 2:* Comparison of qubit technologies and their scalability challenges**

Qubit Technology	Scalability Challenges	Current Status	Potential Advantages
Superconducting (Chakraborty & Joshi, 2024)	Needs cryogenic cooling; decoherence issues	Widely used by IBM, Google	Fast gates, mature tech
Trapped Ion (Anferov et al., 2024)	Hard to scale; precise lasers needed	Used by IonQ, Honeywell	High fidelity, long coherence
Topological (Anferov et al., 2024)	Unproven; stable anyons not realized	Experimental (e.g., Microsoft)	Intrinsic error resistance
Photonic (Anferov et al., 2024)	Photon loss; hard long-distance entanglement	Early emerging field	Long-range quantum links
Silicon (Gonzalez-Zalba et al., 2021)	Precise electron control; scaling limits	Explored by Intel, others	CMOS compatible, integrable

Although there is considerable promise in terms of quantum computing and scalability, significant challenges remain in building a scalable quantum computing system that is both practically useful within a real-life timescale and functionally useful. Communication and soundness issues, fabrication, and needing cryogenic temperatures to run qubits are fundamental and significant challenges that prevent improved design and adaptability of quantum systems. Nevertheless, simultaneously, improvements in quantum error correction, qubit noise, and current quantum hardware research are progressing at a rapid enough pace that these challenges will be overcome in the future.

6. Conclusion

Quantum computing technology has potential to redefine sustainability energy-efficient technology in legacy computing architecture. The concepts of green computing, superposition and entanglement, will improve sustainability energy efficiency. Algorithms such as: Shor's, Grover's algorithm, the quantum approximate optimization algorithm (QAOA), and quantum simulation, will constrain upper bounding time and power limitations for cryptography, database search, optimization, and modeling complex systems. Implementations such as energy system scheduling, materials discovery, and quantum enhanced machine learning create a pathway toward sustainability. However, the current hardware is still in the Noisy Intermediate-Scale Quantum (NISQ) era and has many obstacles to overcome with respect to DE coherence, cryogenic cooling, and large error-correction overhead. More qubit fidelity, material science, fault-tolerance, and quantum-classical hybrid approaches would still be needed to provide significant energy savings. In conclusion, quantum computing provides a huge opportunity for future work around sustainable computing. If both the algorithms and hardware improve, quantum computers could provide meaningful energy savings in the energy envelope for data-centric computing ultimately.

7. Conflict of Interest

The authors declare no conflict of interest.

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