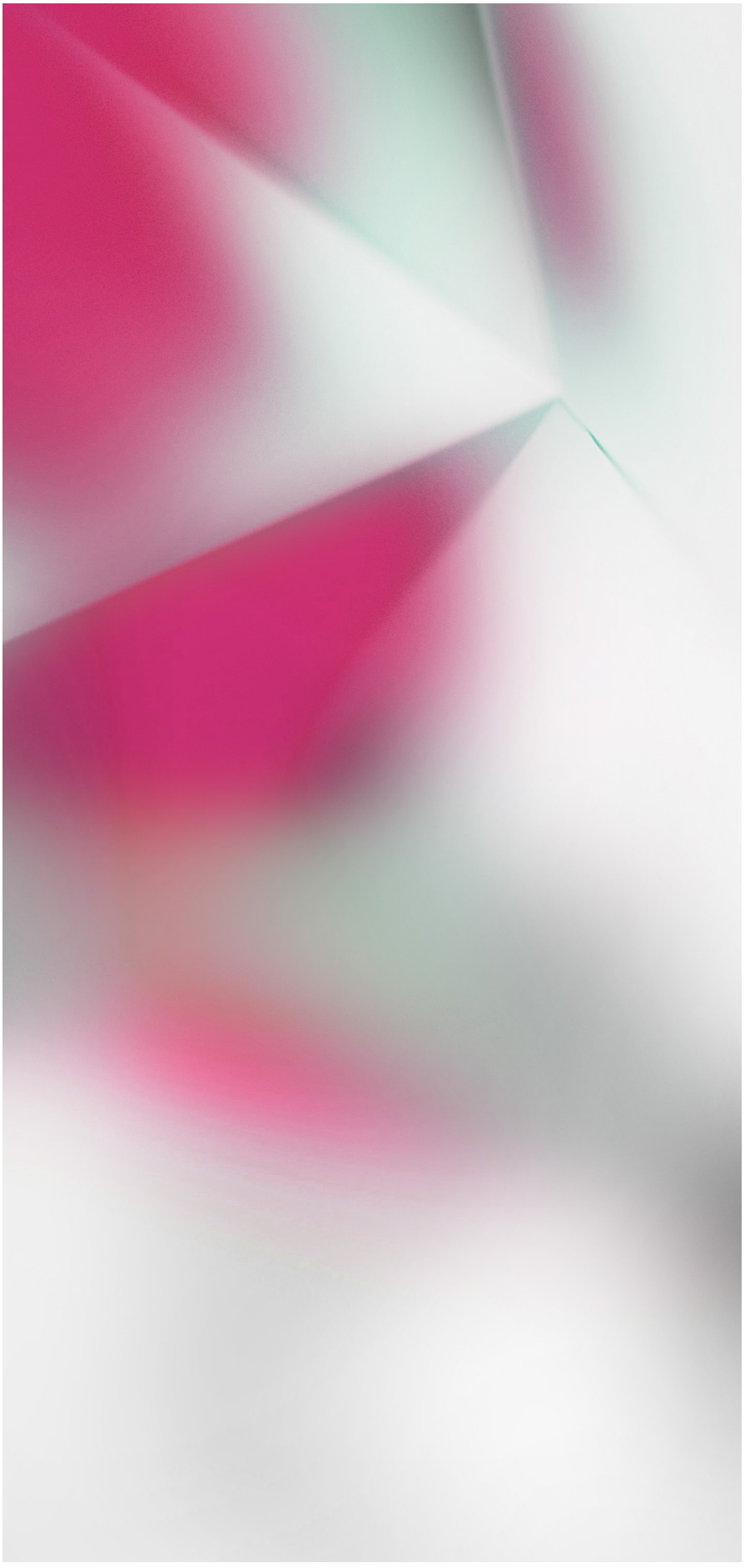
Quantum Computing for Energy Grid Optimization

Where Quantum meets the Grid:

Possibilities, Progress, and Practical Limits

qBraid

SOUTH CAROLINA QUANTUM



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Overview

Energy systems are becoming increasingly complex. In the United States, nearly 10,000 electricity generation units are connected by more than 300,000 miles of transmission infrastructure, with a combined capacity exceeding one million megawatts. This energy flows through regional grids that remain vulnerable to outages caused by weather, aging infrastructure, and system inefficiencies. These disruptions carry both operational and financial consequences.

Forecasting and balancing supply and demand are growing more difficult. The accelerating integration of renewable energy, growing electrification across sectors, and changes in consumption patterns have made systems harder to predict and manage. These dynamics introduce high-dimensional, interdependent optimization problems that are computationally intensive to solve using classical methods. Quantum computing is emerging as a possible tool to address some of the bottlenecks faced by traditional approaches in energy optimization.

This report examines key energy optimization challenges and explores how quantum computing may help solve them. Case studies and comparative results are included to provide real-world context.

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This white paper is part of a commissioned series from SC Quantum examining real-world case studies of quantum technologies deployed in industry. Developed in collaboration with qBraid, the series offers insight into how forward-looking organizations are integrating quantum solutions into their operations today. South Carolina Quantum (SC Quantum), a 501(c)(3) established in 2022, brings together academia, entrepreneurs, industry, and government to develop collaborative solutions that strengthen the state's position in a rapidly evolving field. https://qbraid.com | https://scquantum.org

01 - Trends and Challenges in the Energy Sector

The energy sector is undergoing a rapid transformation. The move to renewable energy, the expansion of electrification, and the digitization of infrastructure through smart grid technologies are reshaping how energy is produced, delivered, and consumed. These trends are introducing new layers of complexity for system operators, planners, and investors.

1. Variability in Renewable Energy Supply

The transition from fossil fuels to renewable sources like solar and wind is essential for meeting sustainability goals. These sources, however, are inherently variable and weather-dependent, which makes them difficult to forecast with high accuracy. This intermittency poses challenges for traditional energy models that rely on predictable generation patterns.

Bringing more renewables onto the grid requires precise modeling of energy conversion and supply availability. Grid operators must be able to manage sudden drops or surges in output, which adds complexity to balancing supply with real-time demand. These challenges become more critical as renewable penetration increases, since grid flexibility and forecasting precision are key to maintaining stability.

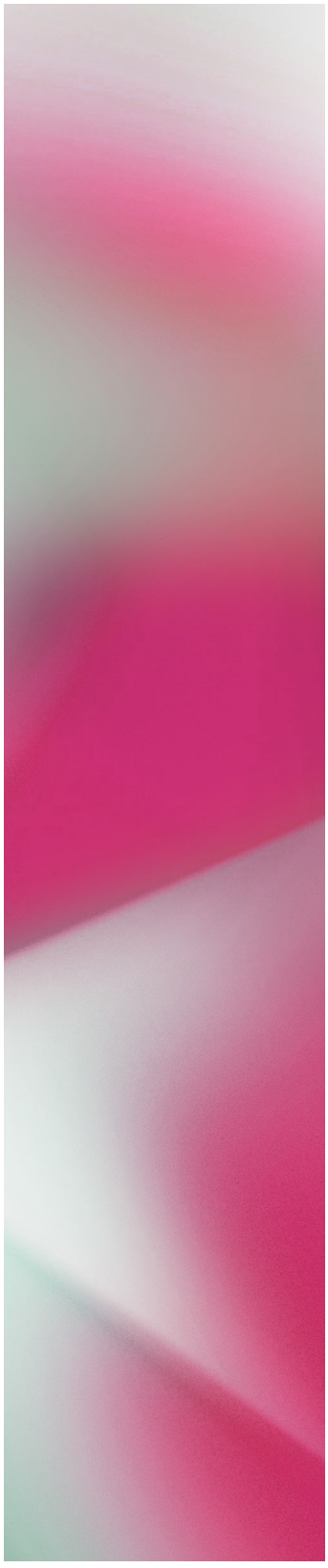
2. Electrification and Demand-Side Complexity

On the demand side, electricity consumption patterns are becoming more volatile. The adoption of electric vehicles (EVs), smart appliances, heat pumps, and other electrified technologies has introduced new variability in when, where, and how electricity is used. For example, EV charging behavior can shift widely by user, location, and time of day, making demand forecasting and load management more difficult.

Data centers now consume over 1% of the world's electricity, a figure expected to rise sharply with the growth of AI and cloud computing. These load centers not only draw enormous amounts of power but also require an ultra-reliable, uninterrupted supply, which further stresses system reliability and operational planning. Modeling and forecasting electricity demand in this context requires handling dynamic, high-resolution data and making real-time optimization decisions under uncertainty. These problems can quickly become computationally intractable using conventional tools.

3. Grid Reliability and Fault Detection

As grid infrastructure expands and becomes more interconnected, maintaining system reliability has become more computationally demanding. Today’s power networks must process a growing stream of real-time data from sensors, substations, and distributed assets to detect faults, localize disruptions, and trigger corrective actions. Fault detection now goes beyond monitoring and often requires solving optimization problems under tight time windows. Identifying minimal corrective actions, reconfiguring power flow paths, and restoring service while staying within grid constraints must all happen quickly and under uncertain conditions. The growth of distributed energy resources adds even more control variables, making classical methods less effective at scale.



While digitalization and smart grid infrastructure provide the raw data and connectivity needed for faster decision-making, they also create pressure. Advanced algorithms are now needed to match the speed and complexity required for resilient grid performance.

4. Optimization at Scale

Across all domains, energy operators face large-scale combinatorial optimization problems. Determining optimal battery dispatch schedules, managing transmission constraints, and aligning generation with stochastic demand all require navigating decision spaces that grow exponentially with system size. These challenges point to the need for more advanced computational tools. Traditional methods are reaching their limits. As grid complexity continues to grow, the sector must consider new technologies that can address scale, uncertainty, and real-time responsiveness at once.

02 - Challenges for Classical Computing

As the energy sector moves toward deeper electrification and greater renewable integration, system operators face a sharp increase in decision variables. These variables exhibit nonlinear interactions and temporal dependencies that significantly increase the dimensionality and computational burden of planning and operations models. Real-world optimization problems involving tens of thousands of variables and constraints can take more than 15 hours to solve on classical CPUs for a single iteration.

Common fault detection methods like Principal Component Analysis (PCA), Fisher Discriminant Analysis (FDA), Partial Least Squares (PLS), and Independent Component Analysis (ICA) often struggle to handle high-dimensional, nonlinear system data. More advanced approaches, such as deep learning and support vector machines (SVMs), can improve performance. Still, they often require deep architectures and significant compute resources, which makes them difficult to scale.

These challenges are compounded by the slowing of Moore's Law. As transistor sizes approach angstrom-level dimensions, the historical trend of doubling compute power every two years is flattening. This creates added pressure for the energy sector, which can no longer rely on steady hardware gains to keep up with growing computational demands.

This growing complexity has created a gap between the demands of modern energy problems and the capabilities of classical computing systems.

The challenge is not just the number of variables, but the complexity of modeling and optimizing them jointly. Quantum computing does not automatically simplify these problems or absorb additional variables on its own. Its value lies in the ability to deliver meaningful speedups for specific classes of problems, most notably in combinatorial optimization, linear algebra, and quantum simulation.

When energy system problems can be reformulated into quantum-compatible structures such as quadratic unconstrained binary optimization (QUBO) models or variational quantum circuits, quantum algorithms can explore exponentially large solution spaces more efficiently. This can reduce the computational strain that classical methods face as system size and complexity grow.

03 - Quantum Computing Use Cases

Quantum computing is beginning to offer practical tools for addressing high-dimensional, nonlinear, and combinatorially complex problems in the energy sector. Approaches such as quantum annealing and hybrid quantum-classical algorithms are showing early promise. While the technology is still emerging, results across several areas suggest that quantum methods may have a meaningful role to play.

1. Renewable Energy Forecasting and Grid Optimization
Forecasting solar and wind generation requires the integration of weather models, sensor data, and historical performance. These datasets are large, dynamic, and highly interdependent. Recent studies have shown that quantum machine learning models, such as quantum long short-term memory (QLSTM) networks, can outperform classical LSTM models in both training speed and prediction accuracy for short-term solar energy forecasts. These improvements give grid operators a better ability to anticipate renewable variability and adjust operations in advance.

2. Real-Time Grid Management
Balancing supply and demand, minimizing congestion, and rerouting power are growing challenges as distributed energy resources become more widespread. Quantum systems, especially annealers, have been tested in grid optimization projects to model decentralized routing and reduce congestion. Early field tests by TNO and NREL using quantum-in-the-loop approaches have shown faster computation times and improved grid resilience compared to conventional solvers, particularly in microgrid or localized environments.

3. Energy Storage Optimization and Demand Response
Coordinating distributed batteries and flexible loads in real time is essential for maintaining grid stability. Quantum algorithms have shown potential for quickly evaluating complex scheduling and dispatch scenarios, helping to align renewable generation with consumer demand. Hybrid quantum-classical frameworks tested in residential energy management and microgrid settings have demonstrated improved load balancing and faster optimization compared to traditional solvers.

4. Facility Location and Energy Infrastructure Planning
Deciding where to place wind farms, battery hubs, or solar installations often involves solving a quadratic assignment problem (QAP), one of the most challenging problems in optimization. Quantum annealers have been shown to solve medium-sized QAP instances faster than classical solvers, which can take excessive time or fail to converge. This capability supports more cost-effective and resource-aligned infrastructure placement decisions in both grid planning and energy logistics.

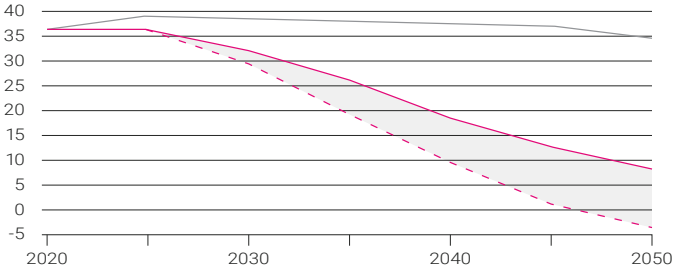
5. Materials Simulation and Energy System Innovation
Quantum simulations are helping accelerate the design of next-generation energy technologies. In solar energy, they support the development of high-efficiency perovskite cells, which could cut costs by up to 50%. In green hydrogen, quantum models of electrolyzer dynamics and catalyst-membrane interactions may improve efficiency and reduce production costs by as much as 60% when paired with advanced solar. Quantum-enabled enzyme modeling may also support low-energy ammonia synthesis, offering a cleaner alternative to fossil-based methods and contributing to a potential 0.4 gigaton CO_2 abatement by 2035. These innovations position quantum computing as a key tool for next-generation, low-emission energy innovation.

6. Sensor Optimization
Sensors are essential for monitoring grid performance, tracking emissions, and ensuring pipeline integrity. Quantum algorithms can help optimize sensor placement and improve data interpretation, particularly in dynamic or resource-limited settings. This applies to both classical sensor networks in use today and future systems that may incorporate quantum sensor data as the technology develops.

While quantum computing shows real promise, it is not a universal solution. In some use cases, such as unit commitment and heat exchanger network synthesis (HENS), both of which involve large-scale mixed-integer formulations, classical solvers continue to perform better. Quantum solvers have matched classical accuracy in small-scale versions of these problems, but hardware limitations such as low qubit counts, persistent noise, and embedding overhead still pose challenges. As the field progresses, these constraints may ease. For now, classical methods remain more effective for certain large-scale, mixed-integer formulations.

Quantum-Enabled Technologies: Putting the world back on track to be net-zero before 2050

Fig. 01 - **CO_2 emissions forecast,[1]** gigatons



Scenario and implied global warming

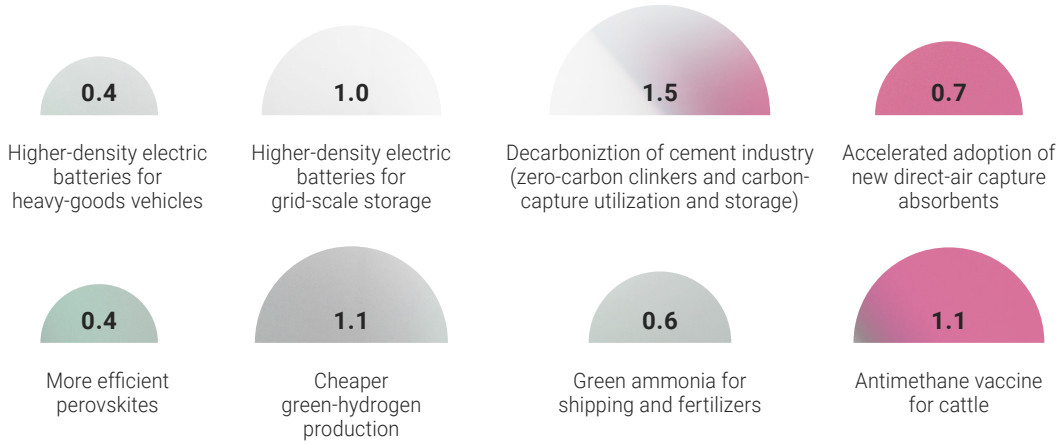
Stated current policies scenario **= 2.2°C**

Sustainable-development scenario **= 1.7 - 1.8°C**

Sustainable-development scenario postquantum impact **= 1.5°C**

Quantum-enabled solutions accelerate net zero to 2050, with 185 gigatons of cumulative-impact increase

Fig. 02 - **Annual additional CO2 quantum impact abatement potential,** gigatons



Figures adapted from: McKinsey & Company. "Quantum computing just might save the planet." McKinsey Digital, April 4, 2022. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-just-might-save-the-planet

04 - Current Developments in Quantum Energy Solutions

In recent years, several research and pilot efforts have advanced the practical application of quantum computing in the energy sector. Projects focused on grid optimization, fault detection, and energy-efficient computing have helped illustrate both the potential and current limitations of quantum systems when compared to classical approaches.

In 2020, Cornell researchers showed that quantum optimization could outperform classical methods in certain combinatorially complex energy problems. While classical computing remained stronger in most cases, the quantum approach demonstrated a clear advantage in facility location planning. In 2021, the Cornell team introduced a quantum-enhanced framework for fault diagnosis by combining deep belief networks with quantum-assisted training. The model achieved high detection accuracy, particularly for subtle system deviations, and showed strong scalability.

Also in 2021, Germany's Federal Ministry of Education and Research launched the Q-Grid project to explore the use of quantum computing for decentralized energy system optimization. The project applied quantum methods to load scheduling, dynamic pricing, and microgrid coordination. Results showed that classical approaches experienced exponential runtime growth even in smaller problem instances, while quantum algorithms such as QAOA and hybrid annealing provided better scaling with comparable solution quality.

In 2023, researchers at the National Renewable Energy Laboratory (NREL) and Atom Computing introduced an open-source interface that connects power grid simulations with quantum processors. By simplifying the translation of grid optimization problems into quantum-compatible formats, the tool enabled early deployment of quantum-in-the-loop frameworks and showed potential for more seamless integration of quantum systems into energy operations.

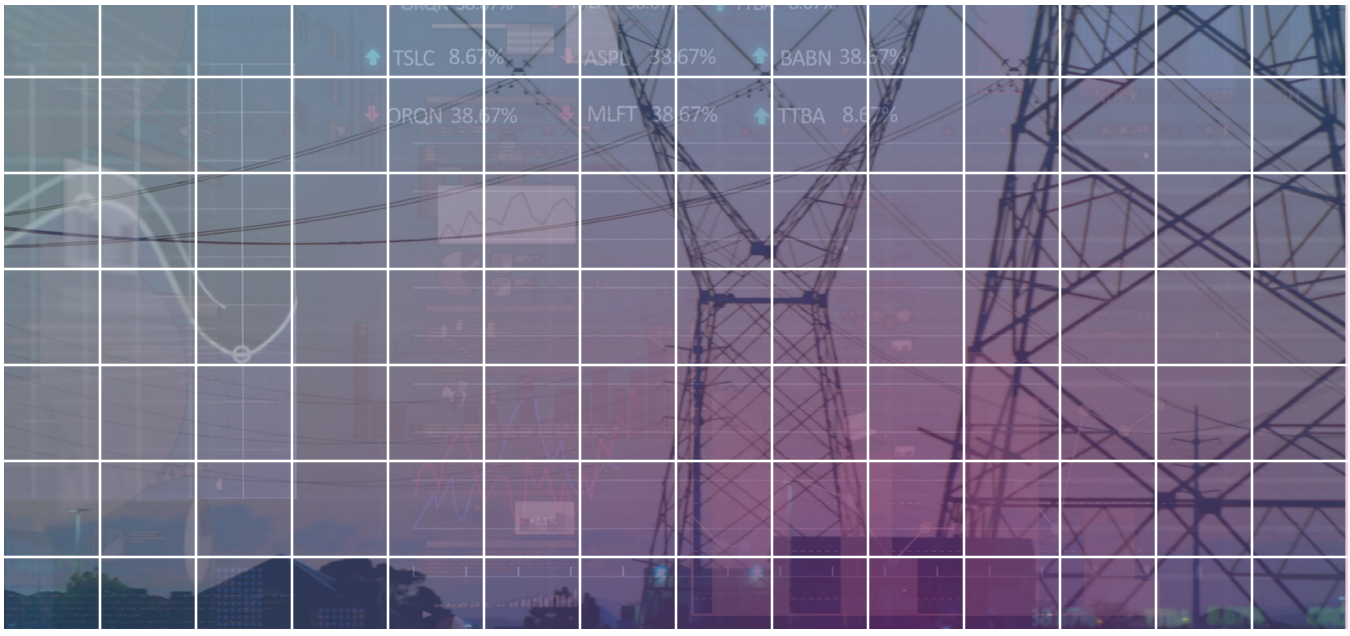
In 2024, Cornell researchers proposed a variational quantum computing–based robust optimization (VQC-RO) framework designed to improve energy efficiency in large-scale AI data centers. By combining variational quantum circuits with classical optimization and reinforcement learning, the model effectively handled uncertainty in renewable generation while optimizing real-time energy use. Simulations showed measurable reductions in both energy consumption and carbon emissions.

In 2025, QuantyMize developed a prototype using quantum annealing to optimize energy production and storage in microgrids. By framing the scheduling problem as a QUBO model, the system reduced battery charge and discharge cycles by up to 40 percent, extending asset life and improving renewable energy utilization.

Together, these efforts reflect a growing body of applied research and early field deployments that show where quantum computing may offer value. They also point to current limitations, including hardware scale and performance variability across use cases, while helping chart a path toward more integrated and production-ready quantum solutions in the energy space.

07 - South Carolina Landscape

South Carolina's energy landscape is changing. The state has a strong foundation in nuclear power, increasing reliance on natural gas, and growing investment in renewable energy. This shift toward a more distributed and variable energy mix brings new operational challenges. Quantum computing could offer strategic advantages in this context by improving renewable forecasting, optimizing storage and grid operations, and supporting the development of clean energy technologies. As South Carolina modernizes its grid, quantum solutions may play a key role in improving reliability, efficiency, and long-term sustainability.



06 - Recommendations

With such a dynamic and rapidly growing landscape, it is important to invest in quantum technologies early. It can be daunting to start, but there are already steps that can be taken.

Here are a few recommendations, if you're on the business side:

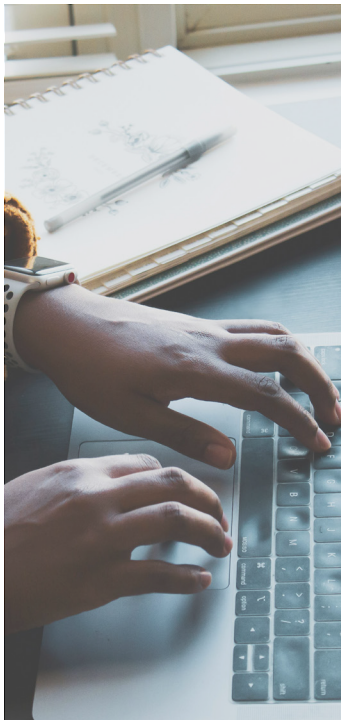
- **Start early:** Don't let caution be the enemy of growth. Foster broad awareness and engagement with quantum technologies among leadership teams and encourage all workers to explore quantum technologies.
- **Build quantum expertise:** Explore and implement training options to ensure your teams are quantum-literate and quantum-ready to create and maintain a competitive advantage through proper use cases.
- **Identify concrete applications:** Become proficient as an organization in evaluating how quantum techniques can help your company meet your goals. Focus on separating hype from reality, and identify clear use cases.

If you're on the technical side, here are a few recommendations to get started:

- **Refresh and develop new skills:** Refresh your quantum skills or upskill by taking courses in quantum mechanics, programming, and applications.
- **Attend conferences:** Quantum computing is a fast-evolving landscape, so meet fellow scientists, researchers, and engineers at conferences. Connect with them to explore collaborations and keep up with research.
- **Connect with domain experts:** Be aware of domain experts and existing work being done in your field. Keep abreast of technological advancements, papers, and patents in your domain.

07 - What's Next?

Exploring quantum technologies for energy grid optimization can seem complex. Collaboration is important in the early stages, and we're here to support you at every stage of your journey. If you're curious or ready to get started, schedule an exploratory call. Ready to dive in? Visit qbraid.com to explore quantum computing, software, and quantum chemistry on quantum computers. With qBraid's interactive courses, cloud-based sandbox, and ready-to-use tutorials, you can run your first quantum job in minutes. To connect with quantum activity in South Carolina and the Southeast, visit scquantum.org. With the right partners, the path can be clearer, more collaborative, and more rewarding than it might seem.



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