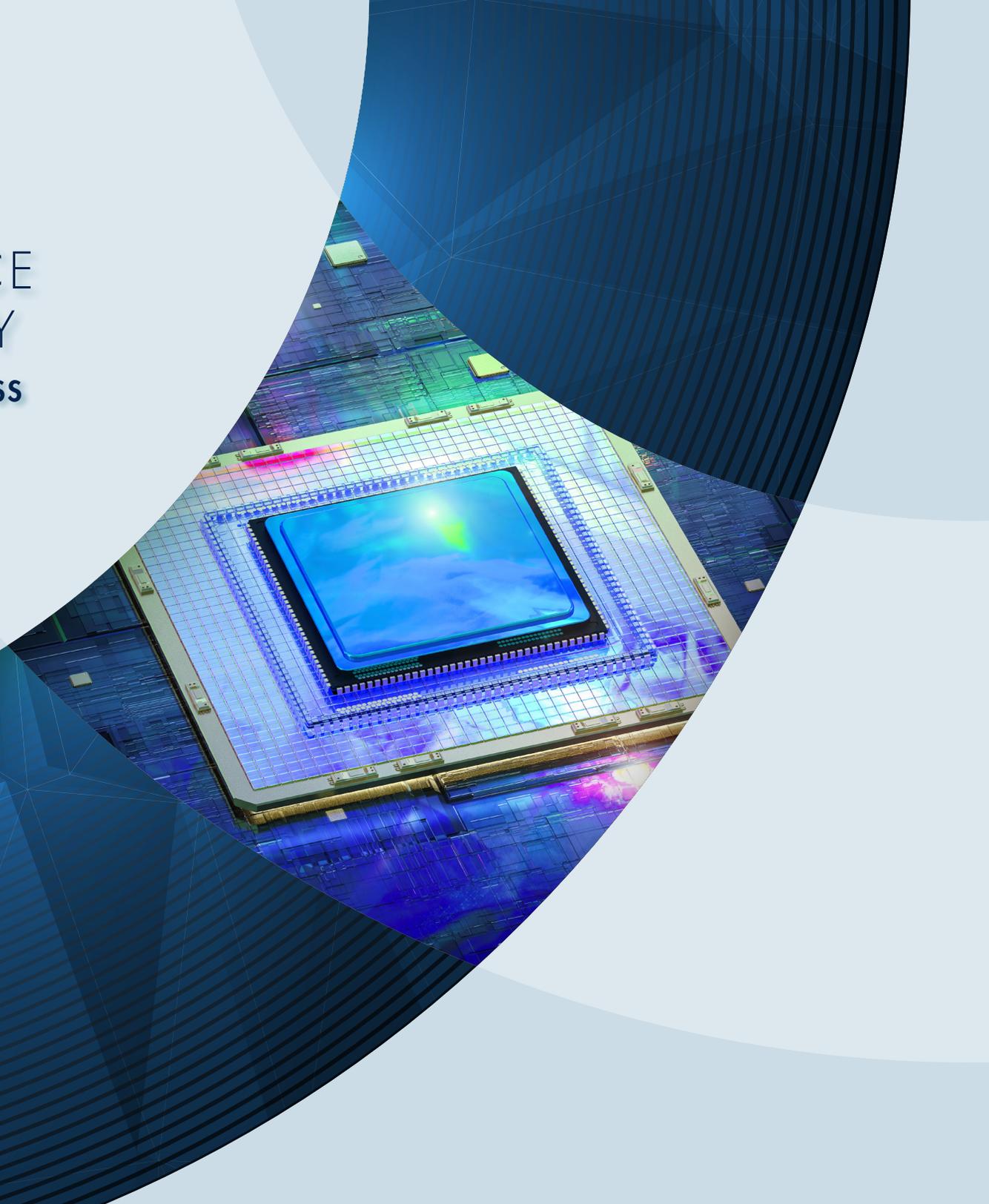# EPRI

QUANTUM SCIENCE AND TECHNOLOGY

2022 TECHNOLOGY UPDATE ACROSS THE ENERGY INDUSTRY

INTRODUCTION

The power grid has been described as the largest and most complicated machine ever built. The expansion of distributed energy resources (DERs), emergence of new loads such as electric vehicles, and increased reliance on intermittent renewable energy generation are transforming the already sophisticated electric power grid into a complex and everchanging network. Keeping this network organized and functioning smoothly and efficiently is becoming increasingly difficult as more diverse assets are added. Modern power systems require a strong computational foundation for data processing to facilitate the constant addition of new loads and energy providers. The need to process such large amounts of data has driven significant research and study including in-depth work by many research institutes, national laboratories, and the U.S. Department of Energy (DOE) to identify the computational needs of the next-generation electric power grid [1].

Quantum computers show promise as an innovative and supplemental computational foundation for the next-generation electric power grid. Many commercial initiatives are being undertaken for development of both hardware and software components to support quantum technology for applications such as cybersecurity, grid optimization, and operations. Although the technology is still nascent, the pace of innovation is accelerating, and the technology may be positioned to disrupt conventional approaches and current applications over the next decade. Quantum computers have the potential to address the needs of the future electric power grid and provide enhanced power system analysis, operation, and control. After decades of gradual research, quantum computers are nearing quantum supremacy—demonstrating that a quantum device can outperform the fastest classical computer—in certain areas. This rapidly evolving technology has many technical hurdles to cross on the road to commercialization, but the next few years may demonstrate its viability and potential impact across industry applications.

Technology developers suggest that quantum computing (QC) will offer solutions in sectors from health care to finance and predict a two-fold impact on the electric utility sector. First, the increased computational power of quantum computing can address complex operational and data intensive challenges—such as cybersecurity, grid optimization, operations, and customer analytics—for a next-generation electric power grid. Second, quantum computers are projected to use significantly less energy than a classical computer per calculation (potentially by several orders of magnitude for select applications), which leads to reduced costs and a decrease to computing's carbon footprint as adoption grows [2]. For example, a modern classical supercomputer such as Summit, housed in Oak Ridge National Laboratory (ORNL), has a processing power of 200 petaflops and has a power capacity of 14 megawatts (MW). Frontier, another classical supercomputer located at ORNL, is 1,100 petaflops (or 1.1 exaflops) and uses 29 MW. This represents a significant improvement compared to Summit in terms of petaflops per MW (14.3 petaflops per MW for Summit versus 37.9 for Frontier, which is more than twice as efficient). A study was conducted comparing Summit to a 53-qubit quantum simulator. In this test, Summit required 21 megawatt-hours (MWh) while a 53-qubit quantum simulation required 4.2×10^{-4} MWh to solve the problem [3]. The test took into account a dilution refrigerator (required to cool the quantum computer to 15 millikelvin) and electronic racks for the quantum computer, making up a total of approximately 0.015 MW of power. The quantum simulation was not able to run error correcting measures but was able to demonstrate a considerable improvement in energy efficiency much greater than the potential cost of adding error correcting measures.

With countless hours of research and analysis, quantum computing has made great strides over the last decade as the pace of innovation is accelerating, moving this technology out of academia and into the commercial arena [4].

THE QUANTUM LEAP

Before discussing potential applications for quantum computing across the energy industry, it is helpful to understand how a quantum computer works, the types of quantum computers, and the developing standards.

Quantum Computing Explained

Classical computers use binary digits, or bits that can be either 0 or 1, as the fundamental component which makes up all other components. Unlike classical computing, quantum computing uses quantum bits, or qubits. A qubit can be any combination of 0 and 1, however, once a measurement is taken, the value of the qubit collapses to either 0 or 1. Thus, only one result is able to be observed. If the measurement is not taken, the quantum system will store the probability of the qubit being 0 along with the probability of the qubit being 1. This is known as superposition, and it allows a quantum computer to execute multiple calculations at the same time. Another fundamental concept, quantum entanglement, is used for the computational process. Quantum entanglement occurs when two or more particles become linked. No matter the distance between the particles they will remain correlated—knowing the state of one can determine the state of the other [5]. The entanglement between particles allows quantum processing to increase exponentially for every qubit, as compared to linearly for every transistor in classical computers. This exponential trend is the underlying cause of quantum computing's remarkable potential to address the problems of the future power grid.

Hardware

There are several types of quantum computers out right now, and research continues to push innovation of these machines forward. The two types which show the most promise today are adiabatic quantum computers and gate-model quantum computers. Adiabatic quantum computers, also referred to as quantum annealers, are available commercially and best suited for optimization problems. Gate-model quantum computers, sometimes called universal quantum computers, are small and many are still in the research phase. Within commercial gate-model quantum computers the qubits are based on different physical architectures. For example, some quantum computers use trapped ions, or superconducting circuits, while others choose to use neutral atom technology. One drawback with using these architectures is that they demand temperatures colder than those found in deep space, because heat can disrupt the qubits. The expensive, bulky cryogenic systems required to hold qubits at such frigid temperatures can also make scaling up these devices to high qubit counts a significant issue—or to create smaller, easier to cool systems. In contrast to architectures such as trapped ions, superconducting circuits, or neutral atoms, quantum computers that depend on qubits based on photons can, in principle, operate at room temperature [6]. However, managing single photons is difficult, and so "squeezed states" consisting of superpositions of photons are used as qubits [7]. The detection of the qubits at the output is based on superconducting detectors at very low temperatures, although research suggests that these low temperatures might not be required for detection when using nonlinear optical materials [8]. The gate-model quantum computers rely on the manipulation of states with the execution of gates—a quantum circuit that controls several qubits. The qubits themselves are very susceptible to external interferences, such as noise, electromagnetic waves, and light. This sensitivity makes it necessary to store these devices at extremely low temperatures and in an environment without these interferences for the quantum computer to run.

Annealing Versus Gate-Model

Some quantum computing companies use a process called quantum annealing to solve complex efficiency problems. Unlike quantum logic gate computers, quantum annealers can utilize more qubits as they are less affected by noise [9]. The qubits in quantum annealers, however, have shorter coherence times. The hardware for quantum annealing is made of building blocks for the Quantum Processing Unit (QPU). These building blocks form a lattice of interconnected qubits made from superconducting loops in their lowest energy state. The superconducting loops in their lowest energy state provide the topology which allows the use of this system for optimization problems. These systems work with binary quadratic models; the optimization problem is mapped to a graph then onto the QPU. Once there, the nodes that represent the variables and quadratic coefficients are described by the coupling strength between the nodes. Solving the optimization problem, in this case, is finding the minimum energy state of the QPU. Companies creating quantum annealers produce more qubits to minimize the effect of shorter coherence times. For example, a quantum annealer set to release in 2023 will have about 7000 qubits and a current gate-model quantum computer has about 128 qubits. Although not as universally suitable, the quantum annealing process shows potential to solve optimization problems. In comparison, gate-model quantum computers are more suitable for applications such as cybersecurity, discovering sustainable catalysts for alternative fuel, and determine binding energies in drug research.

Software

Quantum computing software is deeply rooted in being open source and many of the toolkits are based on Python for its popularity and large open-source-driven community. However, many require support tools to test and implement on specific quantum hardware. Some models and companies have their own unique instruction sets in order to run calculations and tests. The most popular toolkits however aim to be versatile and can be run on multiple different quantum computers at present. Many companies have even set up a cloud-based interface to be able to execute the algorithms on the quantum hardware. The cloud-based tools provided by the quantum hardware companies are also generally Python-based.

Enabling Quantum Technology

The United States Department of Energy (DOE) Office of Science through the National Laboratories leads five National Quantum Information Science (QIS) Research Centers, which aim to foster and facilitate the advancement of QIS and technology applications [8]. Efforts by the DOE, along with early-stage commercial development, highlight several ways that QC can benefit the energy industry and society. In 2021, DOE granted $61 million in funding to the National QIS Research Centers [10] specifically to develop a quantum internet [11]. Additionally, potential public-private partnerships may be undertaken to better explore advantages of QC for the industry.

The National Quantum Initiative Act (NQI Act) of 2018 aims to advance the research and development of quantum sciences for the economic and national security of the U.S. [12]. The NQI Act calls for a united approach to quantum research and development efforts across the U.S. government by directing the president to implement

a 10-year National Quantum Initiative Program. The NQI Act also authorized the National Institute of Standards and Technology (NIST) to strengthen quantum information and science through partnerships, research centers, and consortia with the National Science Foundation (NSF) and the DOE. NIST's role in the field is to understand the potential for quantum-based technology to transform security and communications technology and to develop necessary measurements and standards procedures to exploit quantum's potential.

Other countries have similar initiatives. For example, the United Kingdom National Quantum Technologies Programme (NQTP) is a $980 million quantum investment program to bring developing technologies into commercial reality for national advantage. The program aims to secure a leading position in quantum for the U.K. while stimulating market growth and engineering supply chains through awards to universities, industrial partners, and start-ups [13]. China also has a robust quantum research program that is driven by the government. The budget for universities and some companies in China to perform quantum science research has reached $10 billion as of 2021 [14]. Another example is Germany, who has added about $2.4 billion to support the quantum computing industry. The money will be spread over four years for the quantum innovation program, with hopes of creating the first German quantum computer [15].

Quantum Computing in the Energy Industry

Quantum science and technology has the potential to offer significant benefit to the current and next-generation electric power systems. Quantum computing can provide viable and valuable solutions to electric industry challenges that cannot be easily or quickly solved by classical systems. For example, grid optimization, chemistry simulation, cybersecurity, real-time digital twins, and climate modeling are modern challenges that require extensive computing capacity in which quantum computers have the potential to address.

There are modern challenges that could be solved with current state-of-the-art quantum technology, such as materials selection for experimentation, carbon capture applications, fusion modeling, and batteries. One of the greatest strengths of QC is optimization. This concept has applicability in the fields of operational optimization, materials degradation, and calculations related to power plant maintenance and replacement costs, to name a few. Researchers in these areas are beginning to create and refine models and collect data to generate potential quantum solutions. Some examples of these research endeavors are discussed further.

Key Industry Impact Areas

Cybersecurity

Cybersecurity is a critical priority for electric utilities and the public. Utilities are becoming increasingly reliant on telecommunication infrastructure and information technology to maintain the stability and security of the electric grid. Quantum cybersecurity—using tools including cryptography, encryption, and machine learning—may present stronger and more attractive opportunities to protect vital infrastructure and private information than are now available with conventional security measures.

On May 4, 2022, the White House established a "Migration to Post-Quantum Cryptography Project" to work with industry partners and develop quantum-resilient technology [16].

Existing microgrid systems depend on a classical key system which is vulnerable to cyber-attacks. Novel methods for controlling the grid are required to accommodate renewable and distributed energy resources whose availability can fluctuate in very short time scales. As such, transmission of data between different control centers needs to be secure and offer very low latency. The simultaneous requirements of both strong and fast authentication mechanisms are difficult to achieve through standard cryptographic techniques. Quantum key distribution (QKD) has been used in smaller studies to achieve secure communication and provides a means of detecting an interception or attack attempt on the communication.

DOE's Oak Ridge National Laboratory and Los Alamos National Laboratory recently led a demonstration of quantum cryptography technology hosted by EPB (formerly the Electric Power Board), a community-based utility and telecommunications company serving Chattanooga, Tennessee. In 2019, the team showed how metro-scale QKD may be used to secure communication for the country's electricity suppliers [17]. A crucial step toward eventually integrating QKD into the national grid, the demonstration proved that QKD systems could operate together while using various underlying hardware and software components [18].

In 2020, the research team at ORNL collaborated with a new industry partner, Qubitekk, a QKD manufacturer and developer. Trials were conducted to experiment with quantum-based technologies that could improve the cybersecurity, longevity, and efficiency on the isolated portions of EPB's fiber-optic network. Qubitekk systems were placed at electrical substations to serve as a pitstop; each system passed the key to the next system. These substations were connected by EPB's fiber optic cable and were equivalent to storage for the QKD system. Storing the QKD systems in substations, surrounded by

buildings, cameras, fences, and other security measures, provided both cyber and physical protection. Severe distance limitations previously prevented QKD from becoming a viable addition to existing grid management techniques. Tests showed the photon can travel about 100 miles before the quantum properties change. This experiment demonstrated that three distinct systems can complete a real-world relay of quantum keys across the city [18].

There are obstacles slowing the development of quantum key distribution which, in theory, are unconditionally secure. Presently, the hardware needed for QKD requires new, dedicated fibers as existing fibers cannot be easily retrofitted with QKD technology. QKD also does not offer transmission source authentication, only the recipient. With the very sensitive security measure of authenticating the recipient to avoid eavesdroppers, also comes an added unintentional risk of denial to the intended target when there are no unwarranted observers along the transmission line [19]. If these problems are addressed and theory can become reality, QKD might further increase efficiency and compensate for fluctuating output from renewable energy sources while simultaneously improving cybersecurity.

Grid Optimization

Grid optimization affects all portions of the electricity supply chain: power generation, transmission, distribution, and consumer demand management. Large-scale optimization is computationally expensive. The computational time required to find the optimal number and distribution of power generation units for a given demand profile grows exponentially with the number of variables in the model. Therefore, to find an optimal operating point for a smart grid, the required computational resources will double every time a new node is added

into the network. In practice, due to the system scale, operators cannot achieve full optimization across their networks [20]. The rise in demand for renewable energy and the deployment of hybrid energy systems calls for optimization methods to balance reliability, availability, efficiency, and cost. Quantum computing can, however, provide significantly faster processing, known as quantum speedup, reducing time for finding optimized solutions over classical computing systems.

Quantum computing can be used to provide an optimized solution for the facility-location allocation problem: determining optimum locations of facilities (e.g., generation assets), such as solar or wind power farms. Selecting the optimum location involves minimizing facility construction, operating, and transportation costs for a given energy demand and resource availability. Optimizing facility locations can also prove to be key in establishing optimal electric vehicle (EV) charging stations across the country, helping to spread the reach of EVs. Another component to this problem is the added layer of bidirectional EV chargers, which could prove beneficial to the grid and offset infrastructure upgrades.

Cornell University has explored the application of quantum computing for energy system optimization problems. As a proof of concept, IBM Q and D-Wave's cloud quantum computing platform was employed to solve simplified problems in various areas of the energy industry. The researchers investigated facility-location allocation for energy systems infrastructure development, unit commitment of electric power systems operations, and heat exchanger network synthesis. For the facility-allocation problem, a systematic study was conducted to solve a quadratic assignment problem for 3 to 20 facilities and locations, using both D-Wave's quantum annealer and CPU-based classical computer. As the number of facilities increased, the time required for the CPU-based classical

computer to reach the best-known solution increased substantially until a time cutoff of 12 hours was reached at the optimization of 15 facilities. The quantum annealer was able to reach a solution much quicker, never hitting the cutoff, for all tests up to 20 facilities in size. However, when the number of locations was greater than 13 the quantum annealer no longer had perfect accuracy. The quantum annealer was close to the best known solution, not deviating by more than 5% from the optimal solution, but no longer calculated the best solution. This is a challenge right now in quantum computing: the much faster speed may come with a sacrifice in precision [21].

Quantum Sensing

The field of quantum sensing is related to the field of quantum computing in the sense that both fields are attempting to utilize the quantum properties of matter. However, the classification of devices and systems to "quantum sensing" has a diverse connotation in literature. Both types of devices, (a) detect quantum properties like a single photon, and (b) utilize atoms, ions, or crystals to measure properties of the environment.

While qubits are building blocks of quantum computing, a large number of specific materials and configurations form the basis of quantum sensing. Even though classical sensing platforms are rapidly advancing, quantum sensing technologies can push their performance beyond the classical sensor systems. For example, a quantum-based photon detector can detect a wider range of light wavelengths compared to classical detectors. An additional benefit provided by quantum sensing is that these sensors have higher sensitivity to small measurements compared to classical counterparts. A National Science Advisory Committee (NSAC) subcommittee for QIS recommended quantum sensing for added safety, such as the use of atom interferometric quantum sensors for isotope identification [22].

Sample applications using quantum sensing systems include atomic clocks, navigation systems, non-destructive analysis, and electric and magnetic measurement devices. Additional devices can measure temperature, stress, and strain which could be applied to the energy infrastructure specifically to overhead power lines, towers, and transformers. The use of quantum sensors in smart buildings and smart grids could improve energy optimization applications as well as additional security that senses the slightest anomalies on the system [22].

Currently quantum sensors can fall short of classical sensors in some instances, for example quantum sensors used for navigation. These quantum sensors provide low bias and high stability, which makes them better suited for long-term inertial navigation compared classical sensors which often drift causing inaccuracies. However, acceleration sensors with a fast measurement rate are required for navigation, and quantum sensors struggle to provide a quick measurement rate and remain precise [23].

Many quantum sensors are available today, but some of them are still at laboratory grade scale requiring additional R&D to bring them to a commercial product. Of the different types of quantum sensors, those based on photonics are more well-developed than other systems since these devices do not require constrained operational conditions—such as a low operating temperature—and have lower material costs.

QUANTUM SCIENCE ENERGY INITIATIVES

Few companies working on quantum computing are doing it alone. Within the energy industry, various partnerships have been undertaken to better explore the potential advantages of quantum computing.

Commonwealth Edison Company (ComEd) is building a network of technology transfer partners to explore new applications for quantum computing and meet the challenges of power systems technologies. Partners include the University of Denver and the Illinois Institute of Technology. Quantum computers could provide greater insight into how power is managed as renewables become deployed at a greater rate. ComEd's Bronzeville Community Microgrid project can be a testing ground for how quantum computing might play a role in deploying distributed energy resources at a local level or across a regional network [24].

Researchers at The Technical University of Denmark (DTU) have become the first in the world to perform calculations which solved the load-flow problem with a quantum computer. Also called a power-flow problem, a load-flow problem serves as a fundamental building block for advanced power grid calculations and is used to calculate the solution of a power system with given inputs. DTU researchers performed these tests on a small and noisy 5-qubit quantum computer with promising results. IBM and DTU will collaborate to tackle the load-flow problem for a power grid comprised entirely of renewable resources [25].

The Dubai Electricity and Water Authority (DEWA) is working with Microsoft Corp. to develop quantum-based solutions to address energy optimization and other challenges where classical computers have limitations [26].

E.ON, a German utility company, partnered with D-Wave to study the effects of quantum computing in optimizing an intermittent grid. An effort that proved effective at finding stability was the simplifying of power grids into meaningful clusters. The process is called modularity in complex network theory and is a computation to find these groups within the grid [27].

The Initiative at Northwestern University for Quantum Information Research and Engineering (INQUIRE) is exploring quantum methods to monitor and model the pace of global climate change. The interdisciplinary consortium is harnessing faculty thought leadership from across university departments such as sustainability and energy, engineering, physics, and astronomy. The Chicago Quantum Exchange, a knowledge hub that facilitates regional quantum research, is also participating in the consortium [28].

Los Alamos National Laboratory, Oak Ridge National Laboratory, EPB, and Qubitekk are developing a way to better secure the power grid using QKD to quickly determine whether a bad actor is penetrating a system. Additionally, researchers from Oak Ridge National Laboratory published detailed research in authentication of smart grid communications using quantum key distribution. The research demonstrated that QKD can be used to improve the security of critical infrastructure [29].

Oak Ridge National Laboratory is also exploring the use of quantum computing for power grid operations applications (like digital twinning through real-time simulations). This is critical as more fidelity of models are introduced and smaller timestep requirements are needed in next generation power grids for real-time simulations. A working group consisting of utilities, power grid vendors, and quantum hardware/software developers (and researchers) has also been formed to deliberate the ongoing research and development in quantum computing, including specifically for power grid applications.

FUTURE RESEARCH

The goal of quantum technology is not limited to developing as many qubits as possible, rather additionally determining what problems can be solved with current quantum computers. Quantum technologies are being developed to find solutions for specific problems in the energy industry. Therefore, some applications, such as grid cybersecurity, may drive early-adoption of quantum technologies, and continue to support technology and application development that may need larger numbers of qubits. The enhanced computing power offered by quantum computers can help improve power management systems, but the solutions are still in early stages.

Currently quantum computers are in what is considered the Noisy Intermediate-Scale Quantum (NISQ) era. The qubits that make quantum computing possible have an unstable nature. Even a minor change in the environment (such as slight changes in temperature, vibrations, noise, and electromagnetic waves) can collapse the qubit, leading to computational errors. Another way to combat this, rather than changing the environment, is using error correction. Error correction is done by encoding redundant bits to build a fault-tolerant system. This presents a massive engineering challenge in addition to the long lead times to acquire exotic components and a shortage of quantum engineers.

Quantum computing shows great promise for efficiency as well as being able to tackle problems deemed to take too long on classical machines. Although young, the field of quantum computing and its applications are growing as more industries are introduced. Awareness is a key to growing this field and driving demand. Furthermore, a new generation of engineers schooled in the intricacies of quantum physics are needed to create quantum computers that can tackle real-world problems. Although timelines vary, researchers believe that quantum computing (with machine learning and automation) has the potential to improve grid efficiency and security across the energy value chain, from generation and transmission to distribution and demand management. In applications from grid optimization to operations to cyber security to customer analytics, quantum computing has the potential to enable the utility industry to do more with data than ever before.

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APPENDICES

Acronyms and Abbreviations

DOE – Department of Energy

EV – Electric Vehicle

NIST – National Institute of Standards and Technology

NSF – National Science Foundation

NQI Act – National Quantum Initiative Act

NQTP – National Quantum Technologies Programme

QIS – Quantum information science

QC – Quantum computing

QKD – Quantum key distribution

QPU – Quantum Processing Unit

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