The State of Quantum Computing: Applications, Initiatives, Challenges and Ethical Concerns up to 2025

Farial Mahmod
Department of Computer Applications
Chandigarh University
Punjab, India
17bsc1084@cuchd.in

Abstract

Quantum computing has witnessed a remarkable rise in a century from the theories of Quantum Mechanics to solving real-world problems inside and outside the labs. Experimental quantum computation power has been tested to outperform classical computational power by a wide margin [1]. The work presented here highlights the experimental and commercial state-of-the-art applications of quantum computing from 2016 to 2025. The gathered data includes domains of usage, methods, tools, initiatives, inter-governmental cooperation, quantified results and limitations. In recent times, quantum computing has found applications in diverse areas, including agriculture, defense, energy, finance, healthcare, infrastructure, manufacturing and technology. The purpose of this study is to identify the first of its kind use cases of quantum computers and analyze the outcomes.

Keywords

quantum computing applications, quantum computing, quantum computer, quantum technology, government initiatives, quantum computer limitations, ethical concerns

Background

Quantum computing is an emerging technology suited to tackle complex problems beyond a supercomputer's capabilities. It encompasses both quantum algorithms and hardware. A quantum computer is a type of computer that uses the principles

of quantum mechanics to process information. It utilizes quantum mechanical properties, specially superposition (being 0 and 1 simultaneously unlike classical bits) and entanglement to process information via qubits. A qubit (quantum bit) is the fundamental unit of quantum information. In classical computing, a bit can hold information as either a 0 or a 1. However, a quantum bit, referred to as a qubit, can represent both 0 and 1 at the same time, a feature known as superposition. As a result, having two quantum bits allows for four possible states to be placed in superposition, with the possibilities increasing exponentially. For example, with 333 qubits, there are 2^{333} or about 1.7×10^{100} computational states (named as Googol) that can be placed in superposition, which permits a quantum computer to simultaneously examine a wide range of potential solutions to a problem [2]. Emphasizing the importance of quantum technology, the year 2025 has been declared as the International Year of Quantum by the United Nations.
Quantum computing leverages the concepts of quantum mechanics, including superposition, entanglement and quantum tunnelling to carry out computations with enhanced efficiency relative to classical computers for particular problem sets. The potential applications of quantum computing are vast and expanding. We aim to find, combine and arrange existing research and digital publications available around the world to illustrate how quantum computing is being applied worldwide. Classical computers excel at performing structured, sequential calculations; however, their advantages can turn into disadvantages when faced with numerous interdependent variables. In scenarios involving millions of energy assets, shifting weather patterns, and variable market conditions, the potential configurations and computational requirements increase dramatically. For instance, merely doubling the number of variables does not result in a mere doubling of complexity; it can escalate it by millions of times. In extensive optimization challenges, such as those encountered in the energy sector, even the most advanced supercomputers may require years or even centuries to assess all possible combinations.

Objective

The principal objective of this study is to present a comprehensive review of the current state of quantum computing's ground-breaking applications. Secondly, it explores government initiatives and inter-governmental cooperations around the world for research and workforce development. Finally, the paper underlines the current challenges, limitations and ethical concerns regarding the misuse of

quantum computers. For the purposes of the review mapping, the following research questions have been defined:
Q1: What is the current state of applications of quantum computing in major industries?
Q2: Which complex problems have been solved?
Q3: Which governments have taken initiatives and are collaborating with other governments in quantum computing research and skill development?
Q4: What are the current challenges and limitations in developing quantum computers?
Q5: What are the ethical concerns in using quantum computers?

Introduction

Quantum computers are transitioning from experiment to reality. The prime advantage of quantum computing is the exponential computation power over a classical computer. We have arrived already at a place where quantum computing is a useful scientific tool capable of performing computations that even the best exact classical algorithms can't. Quantum advantage means that a quantum computer can run a computation more accurately, cheaply, or efficiently than a classical computer. The term "strategic advantage of quantum computers" refers to the potential benefits that quantum computers could provide to individuals, organizations, or even nations, especially in fields like computing power, problem-solving, and technological innovation. It highlights how the unique capabilities of quantum computing could give a competitive edge in various industries and sectors. A hybrid approach indicates a combination of quantum and classical models. Like a model aircraft in a wind tunnel, simplified models in quantum simulations can teach researchers about how full-scale systems behave. Although a quantum computer is yet to scale as a classical computer, its enormous computation power is full of potential. American technological giant Google's quantum computer, Sycamore, can perform a specific task faster than any classical supercomputer [3]. Furthermore, Google's Willow quantum chip has achieved a groundbreaking advancement in quantum error correction, demonstrating real-time error correction on a superconducting system with arrays of qubits exhibiting longer lifetimes. On the random circuit sampling benchmark, Willow's 105 qubits complete a computation in under five minutes that would require the world's fastest supercomputer, like Frontier, an estimated 10^{25} years - far beyond the universe's age - proving its ability to tackle problems intractable for classical systems [4]. Canadian quantum computing firm D-Wave's Advantage2, a commercial quantum computer already operational in 2025, through its hybrid solver can easily solve problems of up to 2,00,00,00,00 (2 million) variable constraints [5]. Furthermore, it can be accessed online via cloud service from more than 40 countries as of 2025 [6].

Research has been ongoing to completely stabilize and scale quantum computers. In a 2025 experiment, physicists at California Institute of Technology (Caltech) built an array of 6,100 neutral atom qubits - the largest such array ever assembled using tightly focused laser "optical tweezers" to trap individual cesium atoms in a grid [7]. Even at that scale, the researchers maintained quantum coherence for about 13 seconds and achieved 99.98% fidelity in single-qubit operations, showing that large-scale coherence and high-fidelity control can coexist - a key step toward scalable quantum computers [8].

Methodology

1. Research Method

This review implements a Systematic Literature Review (SLR) approach to synthesize existing knowledge primarily on the use cases of quantum computing globally across industries. The methodology follows established guidelines for conducting structured reviews ensuring reproducibility and comprehensiveness in the selection of sources.

2. Data Sources

To incorporate a broad spectrum of research, multiple databases and repositories have been consulted, including:

1. Peer-reviewed journals (Springer, Frontiers, Nature)
2. Open-access repositories (arXiv)
3. Blogs, case studies and white papers from major quantum computing companies
4. Government Publications

Search queries combined keywords such as "*quantum computing applications*," "*quantum computing use case*," "*quantum technology cooperation*," "*quantum computing limitations*," and "*quantum computing initiatives*."

3. Inclusion and Exclusion Criteria

Inclusion: Studies published between 2016–2025 focusing on experimental and commercial use cases of quantum computing
Exclusion: Articles lacking official source or peer review and non-English publications

Quantum Computing Applications Across Industries

Industries directly contribute to the development and growth of a country. When unlocked, the sheer power of quantum computers can boost the efficiency and performance of multidisciplinary industries that are crucial for the prosperity of a country. Quantum computers are promising unparalleled performance across a range of technologies. The global major industries [9][10] in which quantum computing has been applied are:

1. **Agriculture:** Agrifood and Breeding, Smart Farming and Autonomous Vehicle
2. **Defense:** Optimization and Navigation
3. **Energy:** Electricity and Nuclear Power
4. **Finance**
5. **Healthcare:** Pathology, Oncology, Radiomics, Biomedical Engineering and Dermatology
6. **Infrastructure:** Communication, Transportation and Telecommunication
7. **Manufacturing**
8. **Technology:** AI, Automation, Cyber Security and Space

Quantum computers have recently been employed to solve problems in each one of the above-mentioned vital industries. Each industry-specific application with noteworthy achievements of quantum computing have been highlighted in the study gradually.

1. Agriculture

Since the beginning of the human race, agriculture has remained the prime occupation and business model. Harnessing the power of quantum computing can improve crop management, precise data collection (soil moisture, nutrient levels and pest activity), supply chain flow, weather forecasting and climate modeling. Several countries, specially the Netherlands, the United States and India have conducted multi-level research on how to implement quantum computing in the field of agriculture. Sitting on top of a strong quantum ecosystem, several Dutch bodies throughout the Netherlands have been conducting research on how quantum computers can foster agricultural production.

1.1 Agrifood and Breeding

The Animal Breeding and Genomics group (ABG) of Wageningen University and Research (WUR) in the Netherlands has evaluated a number of agricultural challenges that quantum computers have the potential to solve [11]. Quantum computing offers potential speed-ups for solving large-scale linear equation systems in animal breeding and genetics, using algorithms like the Harrow–Hassidim–Lloyd (HHL) to estimate genetic merits in large populations. In agrifood supply chains, quantum optimization algorithms, such as quantum approximate optimization and variational quantum eigensolvers, are proposed to tackle NP-hard problems like routing, inventory management, and transport of perishable goods, with hybrid approaches showing early promise but no real-world implementations yet. Quantum machine learning techniques, including quantum convolutional neural networks, have been explored for analyzing satellite imagery in land-use classification and detecting plant diseases through high-throughput phenotyping, integrating into hybrid pipelines for improved efficiency. Search algorithms like Grover's provide quadratic speed-ups for genome assembly tasks, aiding mutation detection and genetic diversity analysis in breeding.

1.2. Smart Farming

Aiming to optimize crop yields and resource management amid challenges like water scarcity and climate variability, a novel variational quantum computing (VQC) algorithm has been developed and integrated with IoT for precision agriculture in India. This hybrid quantum-classical approach employs components such as the ZZ feature map for encoding agricultural data correlations (e.g., soil quality, weather, and pests) into quantum states, a real amplitudes ansatz for circuit parameterization and quantum gradient descent (QGD) resulting in top-notch optimization with $O(1)$ time complexity. Furthermore, a quantum support vector machine (QSVM) with a Gaussian kernel is utilized for accurate pest and disease classification by mapping data to higher-dimensional quantum spaces. Experiments on datasets for crops such as wheat and rice running on IBM Eagle and IonQ hardware via Qiskit framework have demonstrated superior performance, including 96.26% prediction accuracy, 24-28% reductions in resource usage (water, fertilizers and pesticides) and 24-26% yield improvements compared to classical methods like GWO [12].

1.3 Autonomous Vehicle

D-Wave in collaboration with Staque have developed a commercial hybrid-quantum application to simulate and optimize the movements of autonomous agricultural vehicles on a large scale [13]. This innovative technology tackles the intricate routing issues encountered by autonomous farming machinery, which classical computers find challenging to resolve swiftly enough for real-time decision-making. By utilizing quantum annealing, the application greatly enhances optimization speed, allowing farmers to increase production while reducing costs. The collaboration seeks to transform agricultural resource management, offering solutions that are both faster and more precise than conventional methods. The application receives support from Verge Ag and Canada's DIGITAL Global Innovation Cluster, and it was presented at World FIRA 2025 and Qubits 2025.

2. Defense

2.1 Optimization

The Australian Army partnered with Q-CTRL to investigate the use of quantum computing for tackling operational logistics challenges. The challenge lay in the fact that large-scale optimization problems, such as scheduling and routing thousands of convoys, are computationally demanding, and classical methods often rely on inadequate heuristics. The participants included the Australian Army, which was conducting Exercise Talisman Sabre in collaboration with the U.S. military, and Q-CTRL, a company specializing in quantum infrastructure software. The Army aimed to validate whether quantum computing could enhance convoy logistics by reducing deployment time while adhering to constraints such as convoy size and speed. Q-CTRL employed a hybrid quantum-classical algorithm, dividing 5,000 vehicles into smaller groups and optimizing them using both classical computation and quantum circuits. Their Fire Opal software minimized hardware errors, enhancing quantum execution and increasing the likelihood of achieving optimal solutions by a factor of 12. The solution led to a reduction in deployment time by over two hours compared to classical methods, demonstrating that quantum computing can provide a practical and strategic advantage for military logistics [14].

2.2 Navigation

Submarines require precise calculation and cannot rely entirely either on Global Navigation Satellite System (GNSS) or on traditional microwave-based clocks for accurate timing and navigation. Furthermore, undersea noise causes navigation drift. To tackle such a complicated issue in an underwater environment, a quantum optical atomic clock device named Tiqker has been developed by Infleqtion for the Royal Navy. Designed to be lightweight and small-sized, Tiqker was put on trial by the Royal Navy in an underwater uncrewed vessel, known as testbed submarine XV Excalibura. Utilizing sub-picosecond clock synchronization, the system has demonstrated precision navigation and timing (PNT). Thus, the quantum system allows the vessel to remain submerged and covert for longer that directly contributes to improved undersea mission performance [15].

3. Energy

3.1 Electricity (Power Grid)

Modern energy systems are so extremely complex and expensive around the world that even small percentage improvements in grid efficiency can result in significant cost savings at utility scale. Quantum computing can empower efficient energy storage management, optimal renewable energy integration, precise grid optimization, smartly-designed distribution network and accurate demand forecasting. The World Economic Forum has highlighted multiple potential areas where quantum computing can revolutionize, including renewable energy forecasting, grid management, energy storage and demand prediction [16]. Spearheaded by E.ON in partnership with Ludwig-Maximilians-Universität München and Aqarios GmbH, Q-Grid is a research initiative funded by the German federal government that investigates the potential of quantum computing to create innovative methods for modeling, simulating and optimizing distributed energy trading networks [17].

3.2 Nuclear Power

The Lawrence Livermore National Laboratory (LLNL) leads quantum computing efforts for fusion energy science through its "Quantum Leap for Fusion Energy

Sciences" project, supported by the U.S. Department of Energy, focusing on simulating nonlinear plasma dynamics using frameworks like Koopman–von Neumann operators and Carleman embedding [18]. LLNL has developed quantum algorithms to model linearized Vlasov–Poisson systems and cold plasma wave propagation, implementing them on noisy intermediate-scale quantum hardware to demonstrate accelerations in Hamiltonian simulations for wave-particle and wave-wave interactions. Collaborations via the 2018 Fusion Energy Sciences Roundtable on Quantum Information Science involve organizations such as Los Alamos National Laboratory, Princeton Plasma Physics Laboratory, University of Maryland, NIST, MIT, University of Tennessee, and Oak Ridge National Laboratory to integrate quantum methods into plasma physics and turbulence modeling. These efforts aim to create predictive models for fusion reactors by addressing challenges in strongly correlated quantum materials and high-density plasmas. Overall, LLNL's work emphasizes hybrid quantum-classical approaches for near-term advantages, despite limitations in capturing chaotic dynamics on current quantum devices.

IBM Quantum provides hardware and tools like Qiskit for experimental validation of quantum algorithms in nuclear fusion research, enabling precise modeling of plasma turbulence, particle interactions, and energy states through hybrid quantum-classical simulations. In this framework, IBM's quantum processors handle intensive computations for reactor stability optimization, while classical systems manage preprocessing, as demonstrated by preliminary data showing superior efficiency over classical methods. The organization supports fusion advancements by running simulations on its quantum simulators and actual processors to test algorithms for complex phenomena like stochastic differential equations in plasma behavior. No specific collaborations are detailed, but IBM's open-source resources facilitate broader research integration for parameter optimization in fusion devices. This application highlights quantum computing's potential to accelerate fusion breakthroughs by overcoming classical computing limitations in high-dimensional simulations [19].

The MIT Plasma Science and Fusion Center (PSFC) has developed a mathematical blueprint using Dyson maps to translate classical plasma physics, such as Maxwell's equations for electromagnetic waves, into quantum mechanics formulations for simulation on quantum computers [20]. This framework encodes quantum circuits in qubits to optimize fusion device designs, including vessel shapes, magnet spacing, and component placement, by enhancing understanding of plasma behaviors in magnetic confinement systems. PSFC researchers test these circuits on classical computers initially to accelerate development and reduce trial-and-error in building fusion prototypes. The approach addresses inefficiencies in traditional simulations, enabling faster iterations for improved electromagnetic wave propagation modeling in plasmas. No external collaborations are specified, but the work positions PSFC at the forefront of hybrid quantum methods for practical fusion engineering advancements.

4. Finance

In digital financial transactions, tokens are utilized to ensure security and privacy of online payments. With the help of quantum computing, Quantum tokens have been transmitted across fibre-optic quantum key distribution (QKD) networks. In a trial, Quantinuum and Mitsui have collaborated to generate and transmit ultra-secure tokens (named as Quantum Tokens) [21]. They have successfully transmitted over a 10 km long network in Tokyo, Japan demonstrating secure transaction verification faster than any existing transmission technology.

Designed to harness quantum physics, Quantum tokens aim to prevent forgery and enable transactions to be settled almost instantly. On the other hand, traditional payment systems depend on double-entry bookkeeping to avoid the double-spending of funds. Additionally, Quantum tokens utilize the no-cloning theorem of quantum physics to combat forgeries and double-spending. This mechanism facilitates swift transaction settlements by removing the requirement to check various systems or wait for network confirmations.

HSBC, in conjunction with IBM, has showcased the world's inaugural empirical evidence of quantum computing resolving a practical issue in algorithmic bond trading, specifically in the optimization of requests for quotes in the over-the-counter European corporate bond markets [22]. This groundbreaking development utilized IBM's Heron quantum processor, which is cloud-accessible and integrated with the Qiskit software stack alongside classical computing, to process noisy market data and identify hidden pricing signals that classical techniques tend to overlook. The quantum-enabled algorithm automates the competitive bidding process by enhancing predictions for trade fills at quoted prices, achieving an accuracy improvement of up to 34% compared to traditional approaches on production-scale trading data. This development provides a competitive advantage in financial services by more effectively addressing complex real-time market conditions and risk assessments. As quantum computers continue to scale, this demonstration highlights quantum computing as a near-term frontier for unlocking innovative algorithms in dynamic financial challenges, rather than a technology that is far off in the future.

5. Healthcare

Due to the enormous power of computation, quantum computers pose the potential to analyze vast amounts of data quickly and contribute to drug discovery, genomic analysis, medical image processing and personalized medicine.

5.1 Pathology

Quantum computing has been utilized in the detection of Alzheimer's disease through hybrid classical-quantum neural networks (HCQNNs), which are trained on 6400 MRI scans to classify the condition [23]. The quantum layer within HCQNNs enables efficient dimensionality reduction, allowing for the establishment of precise decision boundaries that classical models find challenging to achieve. This methodology attains an accuracy rate exceeding 97%, outpacing traditional classical models that only achieve 92%. By promoting earlier and more accurate diagnoses, it aids in timely interventions and enhances patient prognoses. Considered as a remarkable achievement in pathology, quantum techniques enhance computational efficiency in managing complex neuroimaging data for the analysis of neurodegenerative diseases.

5.2 Radiomics

In the realm of radiomics, quantum computing significantly advances cancer characterization through the use of positron emission tomography (PET) imaging, where quantum error mitigation techniques enhance model accuracy to between 70% and 75.66%, compared to the 69% accuracy of traditional methods [23]. It effectively manages 16 features while reducing errors. The implementation of hybrid adiabatic quantum computing for emission tomography reconstruction offers scalable solutions for high-resolution medical imaging. These developments enable improved tumor delineation and support adaptive radiotherapy planning by customizing radiation doses for individual patients. This represents 54.3% of quantum computing research in clinical care, highlighting its potential for precision diagnostics.

5.3 Oncology
Quantum computing has played a crucial role in oncology by optimizing treatment protocols through quantum neural networks (QNNs) that effectively differentiate brain tumors, utilizing quantum annealing for feature selection to achieve a balanced accuracy of 74%, which is comparable to the 73% accuracy of classical methods. Quantum-inspired recurrent neural networks (QRNNs) are employed to predict geometric changes in head and neck cancer during radiotherapy, while hybrid models enhance predictions of drug responses, resulting in a 15% improvement in IC50 accuracy [23]. These techniques enable tailored treatment recommendations, minimizing adverse effects and enhancing decision-making in complex clinical scenarios. Additionally, quantum optimization balances radiation doses with toxicity, and quantum machine learning (QML) proficiently classifies cancer subtypes. Oncology constitutes 48.6% of quantum computing applications in clinical specialties, highlighting its transformative potential.

5.4 Biomedical Engineering
Experimental findings on real-world FEA benchmarks show that quantum computing can play a pivotal role in expediting large-scale finite element analysis (FEA) simulations by utilizing variational quantum imaginary time evolution (VarQITE) to address the graph partitioning problem (GPP). This approach minimizes fill-in during sparse matrix factorization, thereby lowering computational expenses associated with solving linear systems. VarQITE conceptualizes GPP as a quadratic unconstrained binary optimization (QUBO) problem, which is then mapped to a qubit Hamiltonian. It variationally approximates the ground state through imaginary time evolution, employing a topology-aware HeavyNeighborsAnsatz that entangles qubits according to the graph structure. This enables an efficient exploration of solution spaces within the noisy intermediate-scale quantum (NISQ) framework. This hybrid quantum-classical methodology integrates smoothly into Ansys's LS-DYNA software, where coarsened graphs are partitioned on quantum hardware such as IonQ's Aria and Forte processors. The results are further refined using a modified classical Fiduccia-Mattheyses heuristic to reduce noise and maintain balance [311].

5.5 Dermatology
In the field of dermatology, quantum-enhanced Inception-ResNet-V1 models are

capable of classifying skin lesions with an accuracy of 98% on the ISIC 2019 dataset. This performance surpasses that of traditional convolutional neural networks, which achieve an accuracy range of 81-97%, by utilizing quantum parallelism for improved feature extraction. In the area of osteoarthritis, hybrid quantum convolutional neural networks (HQCNNs) attain an accuracy of 98.36% in the classification of knee imaging through the implementation of sparse feature selection. This advancement facilitates the earlier detection of degenerative changes in joints. In the realm of cardiology, the combination of quantum circuits with DenseNet-121 results in a 10% improvement in the detection of cardiomegaly on chest X-rays, thus increasing the interpretability of diagnoses. Additional applications include quantum-assisted modeling of tuberculosis treatment dynamics and drug resistance, as well as predictive analytics in spine care for preoperative planning. These diverse applications illustrate the adaptability of quantum computing across non-oncologic medical sectors, enhancing both diagnostic accuracy and planning efficiency [23].

6. Infrastructure

6.1 Communication

Fast and secure communication is a part and parcel of the modern world. The current communication system worldwide is vulnerable due to unpredictable and continuous cyber attacks. Furthermore, quantum algorithms such as Shor's algorithm, have shown the potential to break current encryption methods (such as RSA) given enough computing power. In response to such a data security risk, in 2022 Toshiba test-launched the Quantum Secure Metro Network (QSMN) in London, using Quantum Key Distribution technology (QKD) to secure communications between sites in Canary Wharf and data centres in Slough. This quantum technology relies on the physical properties of light rather than conventional keys to secure data. Inside out, it encodes individual photons with quantum information which then forms the basis of a special encryption key. No amount of computing power has cracked this key so far. As simply observing a single photon changes its state, therefore alerting the system and causing the quantum system to discard the key that's being transferred. As a result, it is resistant to conventional cyber and quantum attacks.

6.2 Transportation

Hundreds of ships fail every year across the oceans to deliver fuel that is crucial to everyday energy needs. Calculating optimal routes for the ships is a complicated challenge. Efficient transportation of LNG requires:
1. Each ship's position must be accounted for on each day of the year
2. The LNG requirements of each delivery site
Considering a few dozen ships, there can be up to $2^{1,000,000}$ possible combinations of various choices when calculating the routes with the help of modern day computers [24]. As that exceeds the entire number of atoms in the universe, classical computers applying state-of-the-art mathematical methods to calculate the routes spend hours in computation, to find a working solution, let alone finding optimized routes. In real world scenario, the following factors add complexity to the problem:
1. Increasing number of fleets
2. Uncertain weather
3. Fluctuating demand
ExxonMobil and IBM Research partnered to address the maritime inventory routing challenge, optimizing daily journeys for a fleet of more than 500 LNG vessels across worldwide oceans while considering delivery needs, weather unpredictability, capacity limitations, and time restrictions at ports [25]. The approach represents this intricate combinatorial problem through Mixed Integer Programming (MIP) and Quadratic Unconstrained Binary Optimization (QUBO) formulations, converting ports into nodes with predetermined demands to facilitate quantum-driven optimization surpassing classical heuristics. Essential tools comprise IBM's Qiskit framework for quantum simulations leveraging the QasmSimulator backend, alongside quantum variational methods including the Variational Quantum Eigensolver (VQE) and Quantum Approximate Optimization Algorithm (QAOA), coupled with classical optimizers such as COBYLA and the Qiskit Optimization module. Experiments reveal that QAOA surpasses in sampling optimal configurations with numerous samples, whereas VQE provides greater success rates with fewer ones, emphasizing the trade-offs in ansatz flexibility and convergence in noisy quantum settings. This fundamental method not only promotes precise or close-to-optimal solutions for LNG transportation but also applies to wider logistical areas such as vehicle routing and ride-hailing, encouraging combined classical-quantum techniques for challenging issues.

6.3 Telecommunication

Maintaining a large and realtime telecommunication system is a computationally expensive challenge. NTT DOCOMO, the top mobile carrier in Japan serving more than 90 million subscribers, struggled with the optimization of paging signals to effectively track mobile devices amidst the escalating network activity from connected devices. To resolve this issue, the company collaborated with D-Wave for a proof-of-concept study, utilizing D-Wave's constrained quadratic model (CQM) hybrid quantum solver to model and optimize paging traffic across 270 base stations categorized into 21 tracking areas in three regions of Japan. The quantum solution significantly outperformed traditional methods, yielding results in just 40 seconds compared to the over a day required by classical computing. Key results included a 15% reduction in paging signals during peak times, enabling the network to handle 20% more active devices without compromising service stability. Following this achievement, DOCOMO is deploying the quantum-optimized configurations to operational base stations and investigating broader applications in areas such as construction coordination and retail optimization, with executives praising the technology's potential to transform efficiency in the telecommunications sector [26].

7. Manufacturing

The research of integrating a quantum computer to solve critical automotive challenges began as early as 2016. German automaker Volkswagen was one of the first automotive brands to test the application of a quantum computer in the automotive industry. In collaboration with D-Wave in 2019, they have demonstrated the world's first live traffic-routing system powered by quantum computing [27]. An algorithm, to be run on a quantum computer, was developed to optimize intense traffic in busy cities. The experiment was conducted by using buses in Portugal's capital Lisbon to predict traffic and generate optimized routes. This resulted in the decrease of waiting time for passengers as optimized routes minimized the travel time for the buses. As a result, harnessing the power of quantum computing led to the efficient handling of traffic flow. The stunning results found in the traffic-routing test ignited their interest to apply quantum computing to solve other complex tasks. They further conducted an experiment in their sophisticated assembly line. As in a paint shop, every vehicle body requires one of the two primer types depending on its final color. The task of swapping between the primer types increases cost and slows down production. To improve the process's performance, they have developed a quantum algorithm. Consequently, their paint shops now run more vehicles per row without decreasing the assembly overall.

8. Technology

8.1 Artificial Intelligence (AI)

Quantum computing can accelerate the development of specialized AI applications. Researchers in China from the Anhui Quantum Computing Engineering Research Center have achieved a significant milestone by utilizing a domestically developed 72-qubit superconducting quantum computer [28]. Named Origin Wukong, the quantum computer has been used to fine-tune a billion-parameter AI model. The experiment was centered on datasets for psychological counseling dialogues and mathematical reasoning, leveraging quantum processing tasks to facilitate parallel execution alongside classical systems. This hybrid approach effectively equipped the classical AI model with a “quantum engine” for improved synergistic performance. Notable results included a 15 percent reduction in training loss for the psychological counseling task and an increase in accuracy from 68 percent to 82 percent in mathematical reasoning. Impressively, even after pruning over 76 percent of the model's parameters, training effectiveness improved by 8.4 percent, demonstrating the efficiency potential of quantum technology. Origin Wukong, inspired by the legendary Monkey King for its versatility, has processed more than 350,000 computing tasks since January 2024. This breakthrough addresses the increasing 'computing power anxiety' in AI development by enabling more efficient models with reduced memory and energy requirements.

This groundbreaking research highlights promising pathways for deeper integration of quantum and AI technologies in large language models in future.

8.2 Technological Automation

Producing precise components requires heavy computation, smooth mechanical design and efficiency. DENSO, a Japanese mechanical components maker, has accomplished its proof-of-concept work to enhance the control of Automated Guided Vehicles (AGVs) on factory floors, achieving a balance between smooth operation, collision avoidance, and production pace. Through the use of hybrid classical-quantum computing with the help of D-Wave, they identified and ranked the optimal paths for AGVs to minimize traffic congestion. This approach prioritized safety while significantly boosting efficiency. The results demonstrated a 15% average reduction in AGV waiting times for clear routes [29].

8.3 Cyber Security

Quantum computing is changing the ground for cyber security. Random numbers are a cornerstone of cyber security. Quantum Origin stands as a groundbreaking quantum random number generator (QRNG) service developed by Quantinuum, recognized as the only provably secure and fully software-deployable solution for bolstering cryptographic security. It harnesses quantum randomness to enhance encryption keys and shield sensitive data from both classical and quantum threats, ensuring a level of unpredictability that traditional random number generators cannot replicate.

At its essence, the service merges a 'Quantum Seed' - developed on Quantinuum's quantum computers through millions of three-qubit entangled circuits and confirmed via Bell tests (like the Mermin game) for high min-entropy (around 0.85) with local classical entropy sources using patented randomness extractors. This approach distills near-perfect randomness with a min-entropy of 1.0 and an error probability as low as 2^{-128}, making the output indistinguishable from ideal randomness, even to adversaries with success probabilities below 2^{-300}.

Unlike hardware-dependent QRNGs, Quantum Origin does not require additional devices or cloud connectivity, enabling seamless integration into existing systems through pre-built APIs and standard interfaces such as Linux's /dev/random entropy pools. The non-secret, reusable Quantum Seed can be shared across devices and reused up to 2^{300} times, facilitating scalable deployment for enterprises that need to rapidly strengthen their infrastructure. Key benefits include future-proofing against emerging cyber threats, demonstrating security leadership, and addressing vulnerabilities in legacy RNGs that rely on deterministic or unproven methods. Overall, it signifies a next-generation quantum cybersecurity foundation, combining quantum non-determinism with classical efficiency for robust, provable protection.

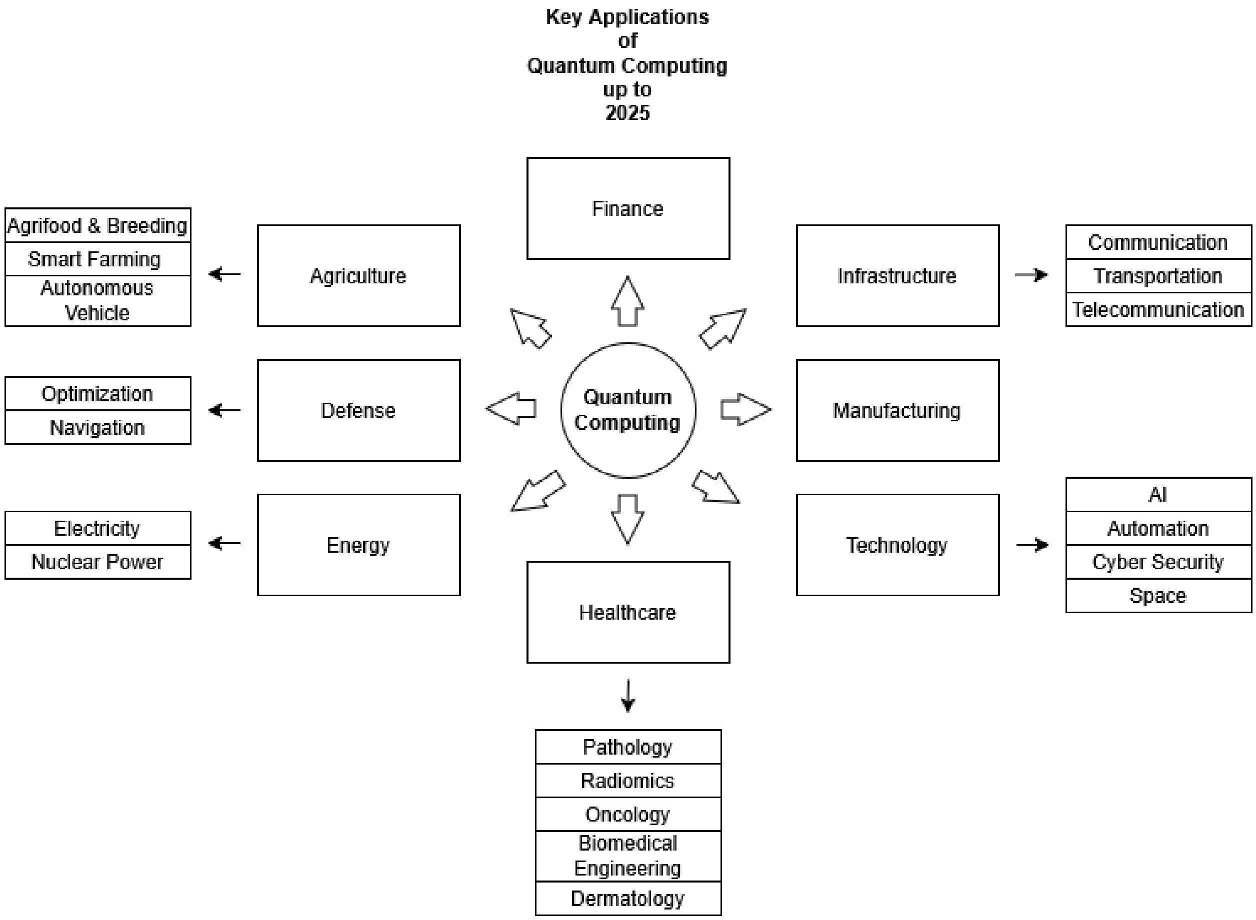
8.4 Space

Philip Walther from the University of Vienna in Austria led a global team of researchers to develop a photonic quantum computer capable of withstanding the extreme environmental conditions encountered during a space mission [30]. For the first time, a quantum processor has been incorporated into a satellite, which is

currently orbiting the Earth at an altitude of approximately 550 kilometers. This mission aims to provide valuable insights into the possibilities of quantum technologies in enhancing tasks and advancing existing technology for space missions.
Quantum computers excel at addressing intricate optimization challenges, which possess a shared mathematical foundation across various sectors. During a live demonstration, DLR Space Operations and Astronaut Training, in collaboration with E.ON Digital Technology, exhibited automated satellite shift planning utilizing quantum algorithms. The tools PintaOnWeb and SQOS (Spacecraft Quantum On-Call Planning) effectively tested quantum-based scheduling for satellite missions. E.ON introduced a hybrid quantum algorithm that is applicable not only to satellite planning but also to smart energy grids, highlighting the potential for cross-sector applications. A key achievement is that these quantum technologies can be integrated into existing systems with relatively minimal effort, marking a significant milestone for future planning in both space and energy sectors. [31]

Findings

Major application areas where quantum computing has been applied as of 2025 are presented below:



Government Initiatives

Governments around the world have set clear roadmaps and have taken steps to invest in quantum computer research and development. Although several quantum computing startups have received private sector funding, government support remains the strategic driving force behind quantum computing research. Global investment exceeds $55.7 billion in quantum technologies as of 2025 [32]. An estimated budget for the development of quantum technologies follows:

Index	Country	Initiative	Amount (USD)
1	China	National Laboratory for Quantum Information Sciences	> 10.0 Billion
2	Germany	Quantum Technologies Framework	3.3 Billion

3	United Kingdom	National Quantum Strategy	3.1 Billion
4	United States	National Quantum Initiative (NQI)	> 3.0 Billion
5	South Korea	National Quantum Science and Technology Strategy	2.3 Billion
6	Japan	Quantum Technology Innovation Strategy	2.2 Billion
7	France	National Strategy on Quantum Technologies	2.0 Billion
8	European Union	Quantum Technologies Flagship	1.1 Billion
9	Russia	Roadmap for Quantum Technologies	> 1.0 Billion
10	Spain	National Quantum Technologies Strategy	880 Million
11	India	National Quantum Mission (NQM)	730 Million
12	The Netherlands	Quantum Delta NL	670 Million
13	Australia	National Quantum Strategy	650 Million
14	Canada	National Quantum Strategy	260 Million
15	Taiwan	Quantum Taiwan Program	250 Million
16	Singapore	National Quantum Strategy (QEP 3.0)	225 Million
17	Denmark	National Strategy for Quantum Technology	170 Million
18	Sweden	WACQT (Wallenberg Centre for Quantum Technology)	135 Million
19	Switzerland	Swiss Quantum Initiative (SQI)	90 Million

[33][34][35][36][37][38]

Inter-Governmental Cooperation

Several governments have partnered to cooperate with each other on the research and development of quantum computers. Bilateral and multi-governmental collaborations involve signing Memorandum of Understanding (MoU), exchanging knowledge and resource and capacity building. The key official agreements include:

Index	Agreement	Parties	Year	Cooperation Area
1	MoU on Quantum Technologies	China and Pakistan	2025	Establishing Pakistan's National Center for Quantum Computing, knowledge exchange and capacity building
2	MoU on the Technology Prosperity Deal	United States and United Kingdom	2025	Cooperation on securing quantum advantage, industry exchanges and joint research
3	Trilateral Quantum Cooperation Framework	United States, Japan and Republic of Korea	2025	Alignment on standards and shared research
4	Joint Statement on Cooperation in Quantum Information Science and Technology	United States and Germany	2024	Emphasizing workshops, data sharing, personnel exchanges and multilateral policy discussions to build inclusive ecosystems
5	Joint Statement	United States and India	2023	Committed to sustaining quantum training, exchange programs and reducing barriers to joint research
6	Joint Statement	United States and Australia	2021	Partnerships in quantum research, infrastructure sharing and policy alignment
7	Joint Statement	United States and Japan	2019	Promoting collaboration in quantum research, development, and talent exchanges

8	InCoQFlag	EU	2018	Research, collaboration and consolidate European leadership in the field of quantum technologies

[39][40][41][42]

Future Directions

Quantum computers not only promise enormous potential but also present challenges and limitations. Additionally, ethical concerns are to be addressed to prevent the misuse of quantum computing.

1. Challenges and Limitations

1.1 High Development Cost: Quantum computers are highly expensive to develop and operate.
1.2 Applicable to Limited Number of Problems: Quantum computers are appropriate only for complex problems that require extensive computation power.
1.3 Limited Accessibility: Quantum computers or quantum computing services are available physically or online in a handful of countries.
1.4 Shortage of Specialized Workforce: Developing and operating quantum computers require expertise in quantum technology that only a handful of experts have worldwide.

2. Ethical Concerns

2.1 Cryptography and Privacy Risks: A quantum computer's ability to break conventionally used encryption via algorithms like Shor's threatens existing data security and privacy
2.2 Access Disparities: Quantum hardware and expertise demand enormous resources that only wealthy nations and corporations can afford - widening global digital divides.
2.3 Military Applications: Quantum technologies mirror military risks in various forms raising concerns about an arms race, geopolitical instability and ethical dilemmas.
2.4 Socioeconomic Impact: Unleashing the enormous power of quantum computing

in manufacturing, automation and optimization could displace jobs in multiple sectors affecting lower-skilled workers.

2.5 Environmental Sustainability: Quantum computers require energy-intensive operations that contribute to high carbon footprints and e-waste.

Conclusion

The review study primarily contributes to the understanding of the multifaceted implications of quantum computing in crucially important industries. The study further explores not only the government initiatives, funding and inter-governmental agreements to foster quantum technology around the world but also underlines the challenges, limitations and ethical considerations.

Grant

This research received no grant from any funding agency of any sector.

References

[1] M. Schuld, V. Bergholm, C. Gogolin, J. Izaac, and N. Killoran, "Demonstration of quantum advantage in machine learning," *npj Quantum Information*, 2018. [Online]. Available: https://www.nature.com/articles/s41534-017-0017-3

[2] Pichai, S., "What our quantum computing milestone means," *The Keyword – Google Blog*, Oct. 23, 2019. [Online]. Available: https://blog.google/technology/ai/what-our-quantum-computing-milestone-means/

[3] F. Arute *et al.*, "Quantum supremacy using a programmable superconducting processor," N*ature*, vol. 574, pp. 505–510, 2019. [Online]. Available: https://www.nature.com/articles/s41586-019-1666-5

[4] H. Neven, "Meet Willow, our state-of-the-art quantum chip," Google Blog, Dec. 9, 2024. [Online]. Available: https://blog.google/technology/research/google-willow-quantum-chip/

[5] D-Wave Quantum, "D-Wave introduces new hybrid quantum solver at Qubits 2024 to tackle customers' previously intractable workforce, manufacturing, and logistics optimization problems," *Press Release*, 2024. [Online]. Available: https://www.dwavequantum.com/company/newsroom/press-release/d-wave-introduces-new-hybrid-quantum-solver-at-qubits-2024-to-tackle-customers-previo

usly-intractable-workforce-manufacturing-and-logistics-optimization-problems/
[6] D-Wave Quantum, *D-Wave Advantage2 Data Sheet*, 2025. [Online]. Available: https://www.dwavequantum.com/media/3ikjqkyw/d-wave-advantage2-data-sheet-final-5_16_25.pdf
[7] "Caltech Team Sets Record with 6,100-Qubit Array," *Caltech*, Sept. 24, 2025. https://www.caltech.edu/about/news/caltech-team-sets-record-with-6100-qubit-array

[8] H. J. Manetsch *et al.*, "A tweezer array with 6100 highly coherent atomic qubits," *Nature*, 2025.
[9] Central Intelligence Agency, *The World Factbook*. [Online]. Available: https://www.cia.gov/the-world-factbook/countries/. [Accessed: Dec. 7, 2025].
[10] Organisation for Economic Co-operation and Development, *Economic Surveys by Country*. [Online]. Available: https://www.oecd.org/en/topics/economic-surveys.html#bycountry. [Accessed: Dec. 7, 2025].
[11] Wageningen University and Research, "Assessing the potential of quantum computing in agriculture," 2023. [Online]. Available: https://edepot.wur.nl/692183
[12] EPJ Conferences, "IEMPHYS 2025 Proceedings," 2025. [Online]. Available: https://www.epj-conferences.org/articles/epjconf/pdf/2025/10/epjconf_iemphys2025_01004.pdf
[13] D-Wave Quantum, "D-Wave and Staque announce new hybrid quantum application for optimization of autonomous agriculture vehicle movements," *Press Release*, 2025. [Online]. Available: https://www.dwavequantum.com/company/newsroom/press-release/d-wave-and-staque-announce-new-hybrid-quantum-application-for-optimization-of-autonomous-agriculture-vehicle-movements/
[14] Q-CTRL, "Improving Army logistics with quantum computing," *Case Study*. [Online]. Available: https://q-ctrl.com/case-study/improving-army-logistics-with-quantum-computing
[15] Royal Navy, "Quantum technology trialled on Royal Navy uncrewed submarine XV Excalibur," *Royal Navy*, 28-Oct-2025. [Online]. Available: https://www.royalnavy.mod.uk/news/2025/october/28/20251018-quantum-navigation-trials-xv-excalibur
[16] World Economic Forum, "Quantum computing for energy forecasting," 2025. [Online]. Available:

https://www.weforum.org/stories/2025/01/quantum-computing-energy-forecasting/
[17] J. Blenninger *et al.*, "Q-GRID: Quantum Optimization for the Future Energy Grid," *Springer Professional*, Aug. 2024. [Online]. Available: https://www.springerprofessional.de/en/q-grid-quantum-optimization-for-the-future-energy-grid/27435440
[18] AIP Publishing, "Quantum computing for fusion energy science," *Physics of Plasmas*, vol. 30, no. 1, 2023. [Online]. Available: https://pubs.aip.org/aip/pop/article/30/1/010501/2867588/Quantum-computing-for-fusion-energy-science
[19] ResearchGate, "Quantum Computing for Nuclear Fusion: Advancing Simulation and Optimization." [Online]. Available: https://www.researchgate.net/publication/387055710_Quantum_Computing_for_Nuclear_Fusion_Advancing_Simulation_and_Optimization
[20] MIT News, "Mathematical blueprint accelerating fusion device development," 2023. [Online]. Available: https://news.mit.edu/2023/mathematical-blueprint-accelerating-fusion-device-development-0622
[21] Quantinuum, "Quantinuum and Mitsui advance unforgeable quantum tokens over fibre network in first-ever trial," *Press Release*, 2025. [Online]. Available: https://www.quantinuum.com/press-releases/quantinuum-together-with-mitsui-advance-unforgeable-quantum-tokens-over-fibre-network-in-first-ever-trial
[22] HSBC, "HSBC demonstrates world's first-known quantum-enabled algorithmic trading with IBM," HSBC News, Sep. 25, 2025. [Online]. Available: https://www.hsbc.com/news-and-views/news/media-releases/2025/hsbc-demonstrates-worlds-first-known-quantum-enabled-algorithmic-trading-with-ibm
[23] Frontiers, "Quantum Computing in Medicine," *Frontiers in Medicine*, 2025. [Online]. Available: https://www.frontiersin.org/journals/medicine/articles/10.3389/fmed.2025.1573016/full
[24] International Business Machines Corporation, "ExxonMobil IBM Case Study," IBM. [Online]. Available: https://www.ibm.com/case-studies/exxonmobil.
[25] International Business Machines Corporation, "ExxonMobil and IBM explore quantum algorithms to solve routing formulations," *IBM Research Medium*, 2025. [Online]. Available:
https://ibm-research.medium.com/exxonmobil-ibm-scientists-explore-state-of-a

rt-quantum-algorithms-to-solve-routing-formulations-e7ce39f8741c
[26] D-Wave Quantum, *NTT Docomo Case Study* V3F. [Online]. Available: https://www.dwavequantum.com/media/wagd4haj/ntt-docomo-case-studyv3f.pdf
[27] Volkswagen, "Volkswagen takes the quantum computing revolution from the lab to the factory," 2021. [Online]. Available: https://www.vw.com/en/newsroom/future-of-mobility/quantum-computing.html
[28] The Quantum Insider, "Chinese researchers use quantum computer to fine-tune billion-parameter AI model," 2025. [Online]. Available: https://thequantuminsider.com/2025/04/07/chinese-researchers-use-quantum-computer-to-fine-tune-billion-parameter-ai-model/
[29] D-Wave Quantum, *Denso Case Story* V6. [Online]. Available: https://www.dwavequantum.com/media/rhelg04q/dwave_denso_case_story_v6.pdf
[30] B. Ralser and S. Herzog, "Quantum computer from Vienna for outer space," *Rudolphina – Research Magazine of the University of Vienna*, 11 Jun. 2025. [Online]. Available: https://rudolphina.univie.ac.at/en/quantum-computer-from-vienna-for-outer-space
[31] DLR Quantum Computing Initiative, "Test run for quantum-optimised mission planning," 2024. [Online]. Available: https://qci.dlr.de/en/test-run-for-quantum-optimised-mission-planning/
[32] Qureca, "Quantum Initiatives Worldwide," 2025. [Online]. Available: https://www.qureca.com/quantum-initiatives-worldwide/
[33] "Benchmarking Quantum Technology Performance: Governments, Industry, Academia and Their Role in Shaping our Technological Future." [Online]. (No link provided).
[34] McKinsey, "The Year of Quantum: From concept to reality in 2025," *McKinsey Quantum Technology Monitor Report*, 2025.
[35] Qureca, "Quantum Initiatives Worldwide 2025," Qureca Report, 2025. [Online]. Available: https://www.qureca.com/quantum-initiatives-worldwide/. Accessed: Nov. 20, 2025.
[36] UK Government, *National Quantum Strategy*, Dec. 2023. [Online]. Available: https://assets.publishing.service.gov.uk/media/6411a602e90e0776996a4ade/national_quantum_strategy.pdf

[37] National Quantum Initiative, *Supplement to the President's FY 2025 Budget*, Dec. 2024. [Online]. Available: https://www.quantum.gov/wp-content/uploads/2024/12/NQI-Annual-Report-FY2025.pdf
[38] P. Tripathi, "Global initiatives in quantum computing: The role of international collaboration," Observer Research Foundation, Sep. 19, 2023. [Online]. Available: https://quantum.web.cern.ch/sites/default/files/2023-09/Global%20initiatives%20in%20quantum%20computing.pdf
[39] Ministry of Planning, Development and Special Initiatives, Government of Pakistan, "Pakistan and China sign MoU to enhance cooperation in quantum technologies," Press Release, Oct. 23, 2025. [Online]. Available: https://pid.gov.pk/site/press_detail/30737
[40] Prime Minister's Office, 10 Downing Street, U.K. Government, "Memorandum of understanding between the Government of the United States of America and the Government of the United Kingdom of Great Britain and Northern Ireland regarding the Technology Prosperity Deal," Sep. 18, 2025. [Online]. Available: https://www.gov.uk/government/news/memorandum-of-understanding-between-the-government-of-the-united-states-of-america-and-the-government-of-the-united-kingdom-of-great-britain-and-north
[41] Office of the Spokesperson, U.S. Department of State, "Trilateral quantum cooperation," Sep. 5, 2025. [Online]. Available: https://www.state.gov/releases/office-of-the-spokesperson/2025/09/trilateral-quantum-cooperation
[42] U.S. Department of State, "Joint statement on cooperation in quantum information science and technology of the United States of America and the Federal Republic of Germany," May 22, 2024. [Online]. Available: https://2021-2025.state.gov/joint-statement-on-cooperation-in-quantum-information-science-and-technology-of-the-united-states-of-america-and-the-federal-republic-of-germany/
[43] The White House, "Joint statement from the United States and India," Jun. 22, 2023. [Online]. Available: https://bidenwhitehouse.archives.gov/briefing-room/statements-releases/2023/06/22/joint-statement-from-the-united-states-and-india/
[44] Department of Industry, Science and Resources, Australian Government, "Joint statement of the United States of America and Australia on cooperation in quantum science and technology," Nov. 19, 2021. [Online]. Available:

https://www.industry.gov.au/publications/joint-statement-united-states-america-and-australia-cooperation-quantum-science-and-technology
[45] U.S. Department of State, “Tokyo statement on quantum cooperation,” Dec. 19, 2019. [Online]. Available:
https://2021-2025.state.gov/tokyo-statement-on-quantum-cooperation/