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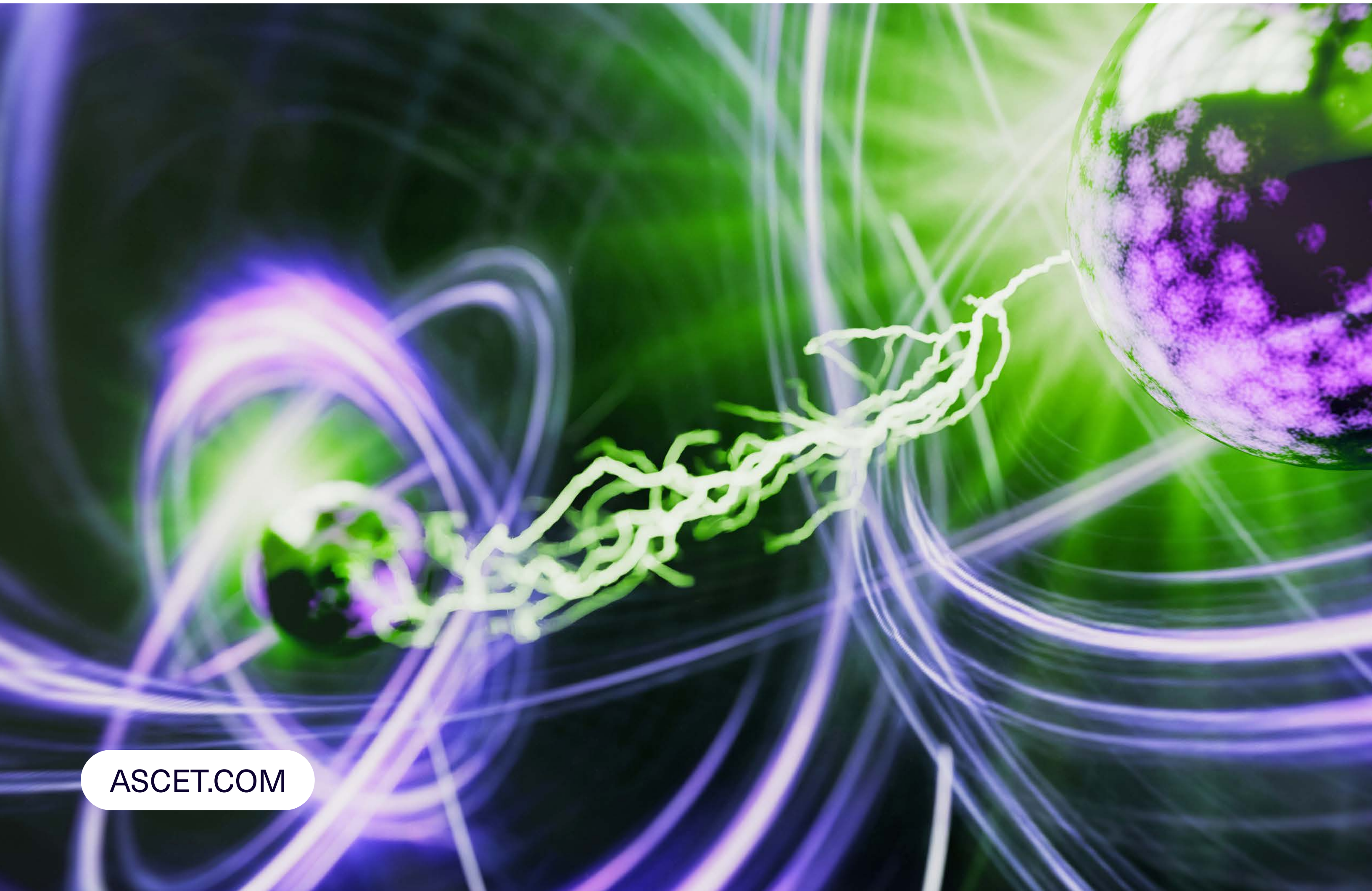
CENTER OF EXCELLENCE

ADVANCING STANDARDIZATION FOR
CRITICAL AND EMERGING TECHNOLOGIES

Standardization Environmental Scan: Quantum Technologies



Purpose and Methodology of the Environmental Scan

This standardization environmental scan provides an overview of how quantum standards are evolving and identifies gaps that could impact U.S. leadership in this critical technology. The scan identifies existing standards, key stakeholders, strategic documents, and emerging gaps to inform future activities such as critical and emerging technology (CET)-specific workshops, roadmap development, and prioritization of standardization efforts. The assessment supports ASCET's broader goal of aligning standardization with U.S. priorities for competitiveness and security, such as ensuring trusted supply chains and accelerating innovation.

This assessment draws on a targeted synthesis of publicly available standards databases, government and industry strategic documents, and stakeholder inputs from government, industry, and academia. The report focuses on standards and initiatives most relevant to U.S. leadership, including those led by U.S. organizations or shaped by international bodies with U.S. involvement.

In addition to identifying areas of maturity and emerging needs, this assessment places particular emphasis on evaluating the pre-standardization landscape—that is, activities that may not yet result in formal standards but are essential precursors to standardization. These include efforts that support component-level testing, reproducibility, interoperability, benchmarking, testbed development, reference architectures, and materials and device characterization. Foundational activities like testbed development and component validation are essential precursors to formal standards. The International Organization for Standardization/International Electrotechnical Commission Joint Technical Committee 1 – Information technology (ISO/IEC JTC 1), the Institute of Electrical and Electronics Engineers Standards Association (IEEE SA), and the Department of Energy's (DOE) Next Generation Quantum Science and Engineering (Q-NEXT) are some of the leading initiatives for foundational activities.[1, 2, 3] Each initiative was evaluated for direct contributions to standards development and its potential to inform future efforts. Analyzing these efforts reveals where quantum R&D is building the infrastructure needed for interoperability and highlights concrete next steps for standards development.

Acknowledgement and Disclaimer

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Quantum information technologies leverage principles of quantum mechanics—such as superposition, entanglement, and interference—to enable new ways of processing, transmitting, and sensing information. These technologies offer potential advantages over classical systems, particularly for solving complex problems that are computationally intensive or require high precision.[4] Quantum information technologies encompass three primary domains: quantum computing, quantum sensing, and quantum communications.[5]

QUANTUM COMPUTING

Quantum computers use quantum bits (qubits), which can exist in a superposition of states—both 0 and 1 simultaneously—enabling new computational paradigms. Quantum computers also have unique components, including quantum processors, superconductors, and quantum software. Due to quantum mechanical nature of the components, these computers process information in ways fundamentally different from traditional lassic computers. While not a universal solution, they provide significantly better calculating and problem-solving abilities for specific, highly complex computational problems, such as modeling behavior for physical systems and identifying patterns in information. As a result, quantum computers are commonly used for chemical and materials science applications. Engineering firms, financial institutions, and global shipping companies are also exploring use cases.[6, 7, 8]

QUANTUM SENSING

Quantum sensors exploit quantum phenomena like entanglement and superposition to measure physical quantities such as time, magnetic fields, and acceleration with unprecedented precision. These sensors are being developed for applications that demand higher sensitivity than classical methods, including infrastructure monitoring, electric grid optimization, microscopy, positioning, timing, and biomedical diagnostics.[9, 10, 11, 12]

QUANTUM COMMUNICATIONS/NETWORKING[13, 14, 15, 16]

Quantum communications use quantum mechanics to protect information and data being transferred. One type of quantum communication is quantum key distribution (QKD) which involves sending encryption keys in a quantum state over networks, while the protected data itself is transmitted over classical networks. Because the act of measuring a quantum state disturbs it, any attempt by a third party to intercept the key is physically detectable. Due to the principles of superposition, hackers struggle to cover their tracks most of the time. Quantum repeaters, quantum teleportation, and the emerging quantum internet are part of this evolving field.

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Current State of the CET Topic: Quantum Technologies

Quantum technologies are beginning to move beyond the laboratory and into real-world applications.[17] The United States is leading the charge in quantum computing—especially with respect to building quantum processing units (QPUs). China currently holds a leading position in quantum communications.[18]

According to Quantum Economic Development Consortium (QED-C), there are 148 companies in the United States that focus solely on quantum. Across North America, about 5,500 people work in quantum-specific roles, and there are over 1,000 open jobs—mostly in engineering, IT, and research.[19]

Public funding for quantum surged in 2024. The National Quantum Initiative Act continues to funnel hundreds of millions into agencies like National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and Department of Energy (DOE). The State of Illinois announced $700 million package of investments, tax incentives, and infrastructure support into building a quantum park.[20] Collectively, governments in the United States have announced a total of $3.2 billion in funding, placing the United States fourth in the world in the amount its government has invested in quantum, trailing Japan, the United Kingdom (UK[21], and Germany respectively). Investments in quantum startups and patents for quantum innovations are led by corporations and universities, which account for 91% of quantum computing patents, with the former accounting for 54% and the latter 37%.[22]

In 2024, the quantum industry achieved a significant breakthrough by stabilizing qubits, which makes the use of quantum technology within mission-critical industries more reliable and thus more viable. Within recent years, other successes include reducing error rates relative to the number of qubits, building quantum control hardware and software, developing multiple high-fidelity qubits, and reducing the cost of quantum error correction.[23] Quantum researchers and companies are now achieving significant advances each quarter.

Quantum technologies made major advances in 2025, including progress toward fault-tolerant, large-scale quantum computing.[24, 25] In early 2025, D-Wave announced that its annealing-based quantum computer solved a complex magnetic materials simulation faster than one of the world's top supercomputers.[26, 27] Microsoft revealed the first prototype processor ("Majorana 1") using topological qubits. [28, 29] Meanwhile, Amazon Web Services introduced a 100+ qubit Ocelot chip.[30, 31] Quantum researchers reportedly achieved improvements in qubit stability and error correction through higher qubit counts (which allows for solving large, more complex problems) and extended coherence times (which improve the reliability and scalability for complex tasks).[32, 33] With respect to quantum communications and security, NIST also added a new quantum-resistant encryption algorithm (i.e., HQC algorithm) to its post-quantum cryptography standards for safeguarding data against future quantum decryption capabilities.[34]

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In early 2026, D-Wave announced a breakthrough in scalable cryogenic control for gate-model qubits which addressed a key challenge in quantum processing scaling by dramatically reducing the wiring needed to control large numbers of qubits without degrading their performance.[35] Around the same time, several quantum companies also went public, signaling investor enthusiasm for recent scientific breakthroughs and the growing perception that quantum technologies are nearing commercial readiness.[36] Researchers also demonstrated the largest quantum-assisted chemistry simulation to date through a hybrid quantum-classical supercomputing experiment; a quantum processor worked in combination with a supercomputer to simulate complex molecular structures.[37] U.S. policymakers also strengthened long-term support for the quantum sector by advancing the National Quantum Initiative Reauthorization Act of 2026 which extends federal quantum programs to 2034 and emphasizes a shift from basic research to practical applications and infrastructure development.[38] This legislation also authorized NASA to pursue quantum technology R&D including quantum-enabled satellite communications and precision sensing initiatives.

As artificial intelligence (AI) has rapidly advanced, senior business executives are quickly becoming “quantum curious”, intrigued by technologies with the potential for transformative impact.[39] AI-driven material discovery can accelerate quantum hardware development, while quantum computing could provide significant amounts of computing power for AI systems. Robotics, cryptography, and cybersecurity are other areas linked with quantum technology.[40]

Standards Landscape Overview

Standards, as defined by the International Organization for Standardization (ISO), are documents that establish a consensus as developed by subject matter experts and approved by a recognized body. Standards provide guidance on design, use, or performance of materials, products, processes, services, systems, or persons. This report will refer to both formal and informal standards, including open protocols, algorithms, technical guidelines, and standardized frameworks.

Establishing standards for quantum technologies is inherently challenging due to the unique properties of quantum mechanics such as superposition and entanglement. Additionally, each subset of quantum technology—including computing, sensing, and communication—requires its own set of standards, which adds complexity to the overall standardization process. To address the uncertainty and complexity introduced by quantum phenomena, new approaches to standards development are being explored.[41]

Standards vary depending on the maturity level of each quantum field. For example, quantum computing is just beginning to approach commercial viability and therefore requires a broader set of standards. In contrast, technologies like superconducting quantum interference devices (SQUIDs) are well established and have more stable standardization needs.[42]

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Post-quantum cryptography (PQC) is currently the most standardized area within quantum technology. Quantum computers may eventually be capable of breaking today's public-key cryptosystems, which underpin digital trust and secure communications. In response, NIST has released several standardized algorithms, marking the first formal quantum-resistant cryptographic standards [43] globally.[43] Multiple standards organizations have formed committees to support PQC development. In comparison, standards for quantum computing, networking, and sensing are still in earlier stages.

Some researchers advocate for consensus-based standards over formal regulations to mitigate risk while fostering innovation. This approach is particularly relevant for quantum technologies, which are still relatively immature. Traditional regulatory frameworks tend to be slow and rigid, making them ill-suited for a rapidly evolving and globally distributed technology like quantum. By focusing on standards—such as benchmarking protocols and technical guidelines—stakeholder can align more effectively and support responsible development.[44]

STAKEHOLDERS

The stakeholders included in the following table were selected based on their demonstrated influence in quantum development, deployment, or standardization. The table captures each organization's role in advancing quantum as a CET as well as their contributions to relevant standards activities. The stakeholders listed account for domestic quantum computers, not international. New acquisitions and funding rounds in 2025 signaled increased confidence in the viability of commercial quantum in the near term.[45] These stakeholders have made foundational advancements in quantum in recent years.

The table separates organizations with a direct or active role in quantum standards development from those included for broader ecosystem relevance but with limited or no current engagement in formal standardization activities.

Stakeholder

ALPHABET INC. (GOOGLE) — MAJOR PLAYER

Role in CET

Google Quantum AI uses superconducting hardware to build their quantum computers. Google has quantum-related partnerships with National Aeronautics and Space Administration (NASA), NVIDIA, and QuEra. In 2024, Google made a major breakthrough by developing [46] a quantum chip that validated the fundamental approach to quantum error correction that will guide Google towards large-scale, fault-tolerant quantum computing. Google Quantum AI has developed open-source quantum software as well, including TensorFlow Quantum, Cirq, and Qualtran.[47]

Role in Standardization of CET

Google was a key contributor to global PQC standardization efforts and works to drive adoption of the standards. Google has contributed to quantum standards developed by NIST, and ISO, and via IEC/ISO JTC 3.[48] Google incorporates

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standardized PQC algorithms into its Google Cloud encryption products and Google servers. Further, the company collaborates with industry and government bodies like NIST to develop quantum encryption-resistant hardware.[49]

Stakeholder

AMAZON/ AMAZON WEB SERVICES — MAJOR PLAYER & EXISTING PARTNER

Role in CET

Amazon Web Services (AWS) manages Amazon,[50] which is a quantum computing service for a variety of quantum hardware technologies and simulation tools. The service incorporates various quantum hardware types from Rigetti Computing, QuEra, IonQ, D-Wave, and Xanadu.[51] AWS revealed its first proprietary quantum chip "Ocelot" in early 2025 which makes progress towards building fault-tolerant quantum computers with real-world applications.[52] AWS also has a center for quantum computing with the California Institute of Technology.

Role in Standardization of CET

Amazon is deploying NIST's post-quantum standardized cryptographic algorithm. AWS released their plan for migrating to post-quantum cryptography. Amazon works with its customers, global standards organizations, and the cryptography community to work towards a quantum future. AWS contributes to international conferences, open literature, and standards development. AWS is part of the following projects and working groups: Internet Engineering Task Force (IETF), ETSI Quantum Safe Cryptography Technical Committee, NIST's National Cybersecurity Center of Excellence (NCCoE) Migration to Post-Quantum Cryptography project, MITRE Post-Quantum Cryptography Coalition, Post-Quantum Cryptography Alliance (PQCA), and the Open Quantum Safe initiative.[53]

Stakeholder

BLUEQUBIT INC. — EMERGING PLAYER

Role in CET

BlueQuibit was chosen to be part of the Defense Advanced Research Projects Agency's (DARPA) Imagining Practical Applications for a Quantum Tomorrow (IMPAQT) program for a project aiming to build quantum artificial intelligence and machine learning [54] Noisy Intermediate-Scale Quantum (NISQ) devices.[55] Other partners include IBM, Honda, Stanford University, Amazon Web Services, Quantinuum, and NVIDIA.[56]

Role in Standardization of CET

In early 2025, BlueQubit joined QED-C as a member organization. Consequently, BlueQubit integrated its quantum computer into QED-C's benchmarking framework for validation. Further, QED-C integrated BlueQubit's software development kit (SDK) into their repository, enabling anyone to run QED-C's benchmarks on BlueQubit's platform. BlueQubit's participation and solidified its technology as accurate and reliable. [57]

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Stakeholder

BOEING[58,59,60,61] — MAJOR PLAYER & EXISTING PARTNER

Role in CET

Boeing is actively advancing quantum communications, sensing, and navigation technologies, with a flagship quantum effort—the Q4S satellite mission—scheduled for launch in 2026. Boeing completed the world's first quantum navigation flight test in 2024 using a quantum inertial measurement unit (IMU) developed with the California-based company, AOSense, which enabled GPS-free flight navigation for over four hours.

In 2023, Boeing contributed $3.5M to the Chicago Quantum Exchange (CQE) to advance quantum communications and sensing including support for early-career researchers, seeding new quantum projects, and sponsoring technical workshops.[62]

Role in Standardization of CET

Boeing collaborates with the steering committees of QED-C and Chicago Quantum Exchange, whose efforts help shape industry priorities for performance metrics, interoperability, and supply chain development.

Stakeholder

IONQ INC. — MAJOR PLAYER

Role in CET

IonQ is a public company producing quantum computing through trapped ions. IonQ's systems are deployed in research labs across the country, including the University of Maryland's QLab. The company has partnerships with Dell, Airbus, Air Force Research Lab, and the Naval Research Lab. IonQ has one of the strongest balance sheets in the quantum sector, with funding ensured for both its computing and networking roadmaps.[63] In 2025, IonQ made a significant breakthrough for quantum networking by transforming visible light into telecom wavelengths capable of transmitting quantum information through fiber optic cables.[64]

Role in Standardization of CET

IonQ participated in a project to make an "application-oriented suite" with the QED-C Standards and Performance Metrics Technical Advisory Committee (TAC). The QED-C Standards TAC released a version of this suite and used it to evaluate leading quantum hardware, including IonQ's quantum computers.[65] IonQ built upon QED-C–style application-oriented benchmarks to create the Algorithmic Qubits (#AQ) metric, which measures a quantum system's algorithmic capability across a suite of representative quantum algorithms.[66]

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Stakeholder

IBM — MAJOR PLAYER

Role in CET

IBM is one of the main pioneers of quantum technology. IBM is responsible for the first cloud-accessible quantum computer.[67] The company has developed a portfolio of quantum computers (using superconducting qubits), open-source tooling, and quantum cloud services. R&D is focused on scalable, fault-tolerant quantum systems with hybrid and modular designs. IBM builds strategic partnerships to promote interoperability and advance quantum-centric supercomputing.[68]

Role in Standardization of CET

As a cornerstone company in quantum, IBM has been involved in many standardization activities. IBM co-developed the first standardized post-quantum cryptography algorithms with NIST, making progress towards protecting cybersecurity systems from quantum's new capabilities.[69] "IBM is among the most transparent firms when it comes to QPU benchmarking. Most of its relevant performance metrics are publicly accessible, including data for individual QPU instances and even individual qubits." [70] The QED-C Standards TAC released an open-source suite and report titled "Application-Oriented Performance Benchmarks for Quantum Computing" and used the suite to benchmark leading quantum hardware, including IBM's quantum computers. [71] IBM includes standardization protocols in its portfolio of IBM Quantum Safe products and establishes partnerships to continue making progress in quantum standardization.[72]

Stakeholder

MICROSOFT — MAJOR PLAYER

Role in CET

Microsoft aims to build scalable, fault-tolerant quantum computers. In 2025, Microsoft revealed the Majorna 1 quantum chip prototype, the first quantum processor built with topological qubits, which demonstrates the ability to harness a new type of material and engineer a new type of qubit.[73] Microsoft has contributed several different quantum products, including a domain-specific programming language, a Quantum Development Kit (QDK) for programming, and Azure Quantum, a cloud-based, hardware-agnostic quantum platform. [74]

Role in Standardization of CET

Microsoft has partnered with NIST, Internet Engineering Task Force (IETF), ISO, Distributed Management Task Force (DMTF), Open Compute Project (OCP), and European Telecommunications Standards Institute (ETSI) on quantum-safe encryption standardization and global interoperability. To help standards development, Microsoft was a founding partner of the Open Quantum Safe project, which aims to "to support the transition to quantum-resistant cryptography" [75] Microsoft has also led integration of the NIST National Cybersecurity Center of Excellence (NCCoE) PQC Migration project and contributed to updating the ISO cryptography standard to include PCQ.

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Stakeholder

NVIDIA — EMERGING PLAYER & EXISTING PARTNER

Role in CET

Similar to AI, NVIDIA aims to build the infrastructure for quantum, rather than the actual products themselves. NVIDIA has invested in multiple quantum startups, including PsiQuantum, QuEra, and Quantinuum.[76] NVIDIA provides classical computing and AI supercomputing hardware and software to quantum developers to prepare and control quantum computers, perform error correction, and analyze results. NVIDIA has also announced a research center for quantum in Boston.[77] The company is establishing partnerships that prioritize hybrid systems using both quantum and classical computing.[78]

Role in Standardization of CET

NVIDIA's investments in quantum lab expansions and hybrid data center facilities position the company to influence early norms and practices in the quantum ecosystem. Working with governments and corporations in research hubs and supercomputing centers also allows NVIDIA to shape future quantum standards.[79] NVIDIA also developed and supports the CUDA-Q quantum programming language, targeting high-performance hybrid quantum-classical applications.[80]

Stakeholder

QUANTINUUM — EMERGING PLAYER

Role in CET

Quantinuum is a company resulting from a partnership between Honeywell Quantum Solutions (USA) and Cambridge Quantum (UK). Quantinuum is the largest integrated quantum computing company in the world. In its most recent funding round, the company raised $600 million in capital, giving the company a $10 billion valuation, likely the highest for a private quantum company. Quantinuum's current spending priorities include expanding commercial systems, R&D, and launching a new *Helios* quantum computer. [81] Partners include JPMorganChase, Oak Ridge National Laboratory, Argonne National Laboratory, and the University of Texas.[82]

Role in Standardization of CET

Quantinuum's Quantum Origin, quantum software designed to provide random numbers for cybersecurity using quantum randomness, received validation from NIST for NIST SP.[83] It was the first such software to receive validation. As a result, Quantum Origin becomes a valuable tool to migrating federal agencies and their partners to post-quantum cryptography standards.[84, 85]

Stakeholder

QUERA COMPUTING — EMERGING PLAYER

Role in CET

QuEra Computing is a private quantum computing company making fault-tolerant, large-scale quantum computers with neutral atoms. In early 2025, the company raised $230 million in funding which will be used for technology development, talent expansion, and increasing scale. Partners and investors include Google Quantum AI, Harvard, Deloitte, Yale, and MIT.[86, 87] QuEra Computing is also responsible for the QuEra Quantum Alliance, which is a global partner program dedicated to advancing neutral-atom quantum computers.[88] BlueQubit, Boston

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Consulting Group, Lawerence Berkley National Labs, and QCWare are partners in the program.[89]

Role in Standardization of CET

In fall 2025, QuEra Computing, Yale, and Harvard introduced a new quantum framework called Algorithmic Fault Tolerance (AFT) which drastically reduces time of error correction in quantum algorithms, ultimately making the prospects of scalability more realistic. Following this research, QuEra Computing recommends government and standards bodies "prioritize neutral-atom approaches and continue supporting initiatives that scale error-corrected architectures aligned with national quantum roadmaps." [90] DARPA selected QuEra for Stage A of DARPA's Quantum Benchmarking Initiative, aimed at building a commercially-useful, fault-tolerant quantum computer within the next decade.[91] As part of the process, QuEra will submit technical concepts and research for independent verification and validation to assess the feasibility of achieving "utility-scale" quantum computing.

Stakeholder

SANDBOXAQ — EMERGING PLAYER

Role in CET

Sandbox AQ uses quantum and AI to advance different scientific areas, including drug discovery, cybersecurity, new chemicals and materials, navigation, and medical diagnostics. The company originally formed within Alphabet/Google but spun off in 2022. Since spinning off, SandboxAQ has raised over $950 million in cumulative funding, including more than $450 million from its most recent Series-E funding round, with investors including NVIDIA and Google.

Role in Standardization of CET

In 2025, NIST added SandboxAQ's Hamming Quasi-Cyclic (HQC) Algorithm to its list of post-quantum cryptography standards. The chosen algorithm is planned to "protect the confidentiality of communications across the internet, cellular networks, payment systems, and more." SandboxAQ also played a significant role in developing SPHINCS+, one of the original algorithms selected by NIST in 2022 in their Cryptographic Algorithm Validation Program (CAVP). Understanding the importance of standardization, SandboxAQ [92] and cryptographic research.[93, 94]

Stakeholder

AMD — EMERGING PLAYER & EXISTING PARTNER

Role in CET

AMD enables quantum through its hardware, including GPUs, CPUs, Radio Frequency System on Chips (RFSoCs), and field programmable gate array (FGPA) technology.[95] AMD has also focused on hybrid systems that combine classical and quantum computing. In 2025, AMD announced a partnership with IBM to develop scalable, open-source hybrid platforms wherein the quantum components simulate the molecular behavior while the classical computing components process large-scale data.[96] AMD has established partnerships with multiple quantum players, including IBM, Elevate Quantum, DOE, and Oak Ridge National Lab.

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Role in Standardization of CET
AMD primarily contributes enabling hardware and hybrid quantum-classical infrastructure; the company does not currently engage directly in formal quantum standards development.

Stakeholder
ATOM COMPUTING —
EMERGING PLAYER

Role in CET
Atom Computing builds gate-based quantum computers with arrays of optically trapped neutral atoms. The company emphasizes scalability, fidelity, reducing complexity, and coherence.[97] Microsoft is one of the company's main collaborators; the two companies worked together to create a reliable quantum computer with neutral atoms. The computer, now available to order, is the first demonstration on record of loss correction in a commercial neutral-atom system.[98]

Role in Standardization of CET
Atom is recognized for technical advances in neutral-atom quantum computing but has not yet participated in formal standardization activities.

Stakeholder
D-WAVE — MAJOR PLAYER
Role in CET

D-Wave is a publicly traded quantum computing company producing both quantum hardware and cloud solutions. The company launched its sixth-generation quantum computer the *Advantage2* in 2024, which is being prototyped for drug discovery, materials science, and national security for Japan Tobacco and Los Alamos National Laboratory.[99] D-Wave offers trial access to start-ups and researchers, which helps broaden quantum adoption and application.[100] In 2026, D-Wave acquired Quantum Circuits to become a key player in gate model computation in addition to their existing annealing computers.[101]

Role in Standardization of CET
D-Wave plays a role in early commercialization and application of quantum computing systems, without current involvement in standards development.

Stakeholder
INFLEQTION —
EMERGING PLAYER

Role in CET
Infleqtion creates neutral-atom quantum technology, including quantum computers, precision sensors, and quantum software.[102] In 2025, the company announced plans to go public through a merger with a "blank-check" company, valuing Infleqtion at $1.8 billion. Infleqtion plans to use merger funding to accelerate R&D and expand applications in areas like AI, national security, and space.[103] Infleqtion has collaborated with DARPA for the IMPAQT program, designed to advance quantum algorithms for machine learning.[104] Infleqtion also received an award from DOE's Advanced Research Projects Agency-Energy (ARPA-E) for using quantum solutions for energy grid optimization.[105] Infleqtion plans to build a neutral atom quantum computer in Illinois as part of $50 million partnership with the National Quantum Algorithms Center and Illinois Quantum & Microelectronics Park.[106]

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Role in Standardization of CET
Infleqtion is active in quantum hardware, sensing, and software R&D, though it does not currently have a direct role in quantum standards bodies.

Stakeholder
PSIQUANTUM — EMERGING PLAYER

Role in CET
PsiQuantum is a quantum computing company focused specifically on creating commercial quantum computers using photonic chips. In 2025, the company raised at least $750 million at a $6 billion pre-money valuation. The company also received significant public funding from Illinois municipalities including the City of Chicago and the State of Illinois. As part of the funding, PsiQuantum and its partners are creating a quantum and microelectronics park on Chicago's south-side with $500 million in public funding.[107] The company plans to produce its first commercial quantum computer by the end of the decade.

Role in Standardization of CET
PsiQuantum is included due to its large-scale investment and system-level development efforts in photonic quantum computing, rather than participation in standards development.

Stakeholder
RIGETTI COMPUTING — EMERGING PLAYER

Role in CET
Rigetti Computing is a publicly traded quantum computing company specializing in superconducting qubit-based processors, hardware, and software. Rigetti Computing has made significant quantum achievements in quantum error correction and chip fabrication. The company collaborates with enterprises, governments, and academic institutions, including Keysight Technologies, NVIDIA, Air Force Research Lab, and Microsoft Azure.[108, 109]

Role in Standardization of CET
Rigetti contributes to the quantum ecosystem through hardware development and research collaborations but is not currently engaged in formal standardization work.

RELEVANT STANDARDS BODIES

This section identifies the key standards developing organizations (SDOs) and consortia actively shaping the quantum standards landscape and highlights their roles in developing foundational terminology, interoperability frameworks, benchmarking protocols, and pre-standardization infrastructure. The organizations profiled include formal SDOs such as IEEE SA, ISO/IEC, and ASTM International, as well as influential consortia like QED-C and industry-led initiatives that contribute to standards through collaborative R&D and testbed development. Each entry summarizes the organization's scope, relevant quantum-related activities, and potential impact on U.S. leadership in quantum technologies.

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EUROPEAN COMMITTEE FOR STANDARDIZATION AND THE EUROPEAN COMMITTEE FOR ELECTROTECHNICAL STANDARDIZATION (CEN-CENELEC)

Role in Quantum Standards

Ensures coherence across international and European standardization efforts: [110] CEN/CENELEC's JTC 22 interacts with international standards bodies including ETSI and ISO/IEC JTC 3 to align on foundational terminology, interoperability, and performance metrics for quantum technologies

European coordination body for quantum standardization: CEN (European Committee for Standardization) and CENELEC (European Committee for Electrotechnical Standardization)—two independent EU standardization organizations—jointly lead European efforts to develop consensus-based standards for quantum technologies, including computing, sensing, and communications

Facilitator of European digital sovereignty and innovation: [111] Supporter of EU policy goals, seeking alignment of quantum standardization with broader strategic objectives including "digital sovereignty" (i.e., defined as Europe's ability to independently develop, deploy, and govern critical digital technologies)

Participates in EU forum for political/technical discussions on quantum (Workstream 16): [112] CEN-CENELEC's JTC 22 contributes to the European Commission's High-Level Forum on Standardization which provides a dedicated platform for political and technical discussions on quantum technologies

Key Initiatives

Developer of European Standardization Roadmap for Quantum Technologies (a.k.a. the CEN-CENELEC Standardization Roadmap on Quantum Technologies): [113] Published comprehensive roadmap in March 2023 using input from 200+ quantum experts across 30 meetings; Identifies gaps, opportunities, and priorities for quantum standardization across domains

Formation of CEN-CENELEC Joint Technical Committee 22 (JTC 22): [114] Formed JTC 22 in 2022 to develop standards across quantum computing, communications, sensing, and enabling technologies; operates through four workshop groups and coordinates with ETSI and ISO/IEC JTC 3 to align on foundational terminology, interoperability, and performance metrics

- **Promotes use of CEN Workshop Agreements (CWAs) for early-stage quantum standardization:** [115] CEN-CENELEC's roadmap recommended the use of CWAs as a flexible mechanism for developing early-stage standardization outputs in areas not yet ready for formal standards (e.g., terminology, interfaces, benchmarking); CWAs enable rapid consensus-building among stakeholders and can serve as transitional tools that bridge research outputs with formal standards development

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Quantum Technologies Use Cases report: Presents nine detailed scenarios across quantum computing, communications, and sensing; each use case highlights specific standardization needs such as hardware-software interoperability, cloud integration, and secure quantum networking; report emphasizes the importance of modular interfaces, hybrid quantum-classical environments, and standardized protocols to support scalable an commercially viable quantum systems; serves as a foundational tool to guide future standards development by identifying where and how quantum technologies interact with broader information and communication technology ecosystems

Workshop on Digital Sovereignty (2023): [116] Hosted dedicated workshop to explore how standardization can support European digital sovereignty; emphasizes that sovereignty in the digital space involves control over data, infrastructure, and governance mechanisms, and that standards are essential tools for operationalizing these principles; the workshop reinforced CEN-CENELEC's commitment to ensuring quantum technologies reflect European values such as privacy, human dignity, and democratic governance and aligned with broader EU goals to reduce reliance on non-European infrastructure and promote innovation through trusted, interoperable systems

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EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (ETSI)

Role in Quantum Standards

Hosts the Technical Committee CYBER Working Group on Quantum-Safe Cryptography (TC CYBER WG QSC) [117, 118, 119, 120] which develops standards and guidance for transitioning to cryptographic systems resilient to quantum attacks; includes hybrid encryption schemes, migration frameworks, and implementation guidance for real-world deployment

Leads the Industry Specification Group on Quantum Key Distribution (ISG QKD) [121, 122, 123] which develops specifications for QKD system interfaces, implementation security, and optical characterization; supports the deployment of secure quantum networks and promotes interoperability across QKD components and systems

Serves as one of the primary European SDOs with central role in quantum communications and post-quantum cryptograph standardization [124]

Key Initiatives

Published over 30 quantum-related standards through the Industry Specification Group on Quantum Key Distribution (ISG QKD) and [125, 126]

- **ETSI GS QKD 016 — Protection Profile for Quantum Key Distribution (QKD) Modules** which enables formal security evaluation of prepare-and-measure quantum systems (ETSI Group Specification Quantum Key Distribution 016 (GS QKD 016) [127]

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- **ETSI TR 103 949 — Quantum-Safe Cryptography (QSC) Migration: ITS and C-ITS Migration Study:** A three-stage migration strategy for Intelligent Transport Systems for transitioning toward quantum-safe cryptography (ETSI Technical Report (TR) 103 949 - Quantum-Safe Cryptography (QSC) Migration; ITS and C-ITS migration study) [128]
- **ETSI TR 104 016 — Quantum-Safe Cryptography (QSC): A Repeatable Framework for Quantum-Safe Migrations:** A repeatable framework for quantum-safe migration which details steps for inventory, risk analysis, and phased implementation (ETSI Technical Report (TR) 104 016 - CYBER; Quantum-Safe Cryptography (QSC); A Repeatable Framework for Quantum-Safe Migrations) [129]
- **ETSI TS 104 015 — Efficient Quantum-Safe Hybrid Key Exchanges with Hidden Access Policies (Covercrypt):** Combines classical and post-quantum algorithms with hidden access policies for secure key exchange (ETSI Technical Specification (TS) 104 015 - Efficient Quantum-Safe Hybrid Key Exchanges with Hidden Access Policies) [130]

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS STANDARDS ASSOCIATION (IEEE SA)

Role in Quantum Standards
Bridge between research and commercialization: Supports transition from open research to commercial quantum technologies; focuses on facilitating interoperability, benchmarking, performance metrics, etc.; maintains some centralized access to active quantum standards projects [131]

Collaborator with global SDOs: Works with ISO, IEC, ITU, NIST, ETSI, and CEN-CENELEC to harmonize global standards across quantum fields; convenes expert working groups across computing, networking, sensing, and hybrid systems [132, 133]

Global facilitator of quantum standards development: Plays central role in conceptualizing and formalizing quantum standards across computing, communication, sensing, and cryptography [134,135]

Key Initiatives
IEEE 3185 – Hybrid quantum-classical computing architecture: [136] Defines hardware and software architecture for hybrid quantum-classical systems which support integration and scalability in emerging computer environments

IEEE P1913 – Software-defined quantum: [137, 138] Defines protocols for configuring quantum endpoints in communications networks, enabling dynamic creation and management of quantum protocols and applications

IEEE P3172 – Post-quantum cryptographic migration standards: [139] Provides recommended practices for implementing hybrid cryptographic mechanisms that combine classical and quantum-resistant algorithms, supporting secure transitions to PQC

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IEEE P7130 – Quantum terminology standards: [140] Defines terminology for quantum technologies to promote clarity and interoperability across computing, communication, and sensing domains

IEEE P7131 – Quantum computing performance benchmark standards: [141] Establishes standardized metric and benchmarking methods for quantum computing hardware and software, thereby enabling consistent evaluation and comparison across platforms

IEEE Quantum Education Portal: [142] For curating educational resources spanning STEM to postgraduate levels; supports workforce development and standards literacy by providing structured learning pathways for students, educators, and professionals entering the quantum ecosystem

IEEE Quantum Initiative: [143] Launched in 2019 under IEEE Future Directions; serves as the central hub for IEEE's quantum-related activities including standards development, conferences, technical communities, and industry engagement; supports multidisciplinary collaboration across computing, networking, sensing, and cryptography; convenes stakeholders through IEEE Quantum Week which includes technical papers, workshops, panels, and career development programs

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INTERNATIONAL ELECTROTECHNICAL COMMISSION / INTERNATIONAL ORGANIZATION FOR STANDARDIZATION JOINT TECHNICAL COMMITTEE 3 (IEC/ISO (JTC 3)

Role in Quantum Standards

Global coordination and integration across quantum domains: [144, 145] Coordinates standardization efforts with related sector-specific committees to ensure consistency and interoperability across applications of quantum technologies including terminology, protocols, and performance metrics

Inclusive international membership and governance: [146] Represents 34 participating countries (P-Members) and 10 observer countries (O-Members) to support board stakeholder engagement and consensus-driven standards development for quantum technologies; held inaugural meeting in May 2024 to set stage for global collaboration in quantum standardization including future plenary sessions and more coordinated international engagement

Primary international committee for quantum technologies standardization: [147, 18, 149] Established in 2024 as the central global body for developing standards in quantum computing, quantum simulation, quantum communications, quantum metrology, quantum detectors, and quantum sources; serves as the foundational platform for harmonizing quantum standards across sectors and geographies

Key Initiatives

Foundational terminology and metrics for quantum: [150,151, 152] Prioritized the development of standardized vocabulary and metrics (i.e., ISO/IEC Joint Technical

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Committee 3, Document 47, New Work Item Proposal - Quantum Photonics Vocabulary [JTC3/47/NP]) for quantum photonics, computing, and sensing to address inconsistencies and overlaps in existing terminology; adopted ISO/IEC 4879:2024 — a foundational standard defining common terminology for quantum computing to support interoperability and consistent communication across the quantum ecosystem which was originally published by ISO/IEC JTC 1/WG 14; *ISO/IEC AWI TR 18157 Information technology — Introduction to quantum computing* is currently under development

Working groups on core quantum domains: [153] Established multiple ad hoc groups (AHGs) focused on key areas including quantum secure communication, quantum sensors, quantum computing and simulation, quantum random number generators (QRNGs), and quantum enabling technologies; as of April 2026, the majority of AHGs have been sunset or converted to Working Groups to formalize participating countries with specific, defined deliverables

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INTERNATIONAL TELECOMMUNICATIONS UNION - TELECOMMUNICATION STANDARDIZATION SECTOR (ITU-T)

Role in Quantum Standards

Coordinates with other international standards bodies including ISO/IEC JTC 3 and ETSI to harmonize international standards [154, 155]

Leads development of quantum key distribution network (QKDN) standards through Study Groups (SG) SG13 and SG17 which focus on network architecture and security [156]

Published foundational standards for QKD network design and management [157]

Serves as the United Nations specialized agency for information and communication technologies (ICTs) [158] with a mandate to develop global standards for quantum communication, quantum cryptography, and quantum-safe networking [159]

Key Initiatives

Developed foundational architecture for quantum key distribution (QKDNs) networks including layered models and integration with classical networks [160]

Developed functional requirements for QKDNs, including quantum layer operations, key management, and control mechanisms [161]

Produced a suite of pre-standardization documents for the formal standardization of quantum information technologies for networks (through ITU-T Focus Group on Quantum Information Technology for Networks [FG-QIT4N]); covers terminology, use cases, protocol specifications, etc. [162]

Produced report providing overview of hybrid key exchange approaches for combining different key exchange methods toward transitioning to quantum-resistant cryptographic systems [163]

CET: Quantum Technologies

U.S. QUANTUM ECONOMIC DEVELOPMENT CONSORTIUM (QED-C)

Role in Quantum Standards

Convenes pre-standardization efforts: Convenes stakeholders to identify technical gaps and coordinate collaborative efforts in quantum research, standards, and workforce development; [164] creates member-led forums that connect technical expertise with emerging standardization needs, particularly in benchmarking and performance metrics [165]

Government alignment: Collects and distributes suggested requirements and benchmarks to U.S. government departments and agencies to support national quantum priorities and commercialization efforts [166]

International standards engagement: Connect its members with global standards bodies to ensure U.S. industry perspectives are represented in international discussions about quantum standards [167, 168]

Technical advisory leadership: Operates multiple Technical Advisory Committees (TACs) and their respective subcommittees; the Standards and Performance Metrics TAC organizes member-led efforts to “enhance the quantum ecosystem” by developing quantum standards including benchmarking methods, interoperability requirements, and terminologies [169]

Key Initiatives

Open-source quantum benchmarking tools: Developed and maintains an open-source suite of application-oriented performance benchmarks for evaluating quantum computing hardware on real-world algorithms and measuring fidelity and execution time across circuit depths and widths using a “framework of volumetric benchmarking” [170]

Post-quantum cryptography (PQC) readiness: Collaborated with financial institutions and quantum technology providers to assess quantum threats to secure messaging and support the implementation of NIST’s PQC standards including federal support for migration and combined approaches using PQC and QKD [171, 172]

Quantum terminology standards: Contributed to NIST IR 8486 (Single-Photo Sources and Detectors Directory) through workshops and expert inputs to promote better understanding and communication of relevant terms and metrics for characterizing single-photon detectors and sources [173]

Standards sub-committee coordination: Facilitates development of performance metrics, benchmarks, interoperability criteria, and architectural guidance by convening stakeholders through its Computing, Network and Sensing, and PIRQ (Practical Intermediate Representation for Quantum) subcommittees, with each focused on distinct aspects of quantum systems evaluation and integration [174, 175]

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EXISTING STANDARDS

Standard Category — Communications Standards:
Networking; Security; Protocols; Cryptography

Prominent Standard	Focus Area/Description
IEEE P1913 (DRAFT)	**Network Architecture:** Describes multi-step processes that can be used to implement hybrid mechanisms (combinations of classical quantum-vulnerable and quantum-resistant public-key algorithms)
IEEE P1943 (DRAFT)	**Security:** Defines post-quantum optimized network security protocols with hybrid key exchange and authentication modes
IEEE P3172 (DRAFT)	**Cryptography:** Provides guidance for transitioning from classical cryptographic systems to hybrid mechanisms that combine quantum-vulnerable and quantum-resistant algorithms; provides guidance for migrating to cryptography that can withstand the threat of quantum computers
ITU-T Y.3800	**Network Architecture:** Provides overview of QKD networks and their integration with user networks
ITU-T Y.3803	**Key Management:** Describes secure key storage, relay, and delivery mechanisms in QKD networks
ITU-T Y.3804	**Network Architecture:** Specifies control and management functions for secure and efficient QKD network operations

Standard Category — Foundational Standards:
Terminology; Metrics

Prominent Standard	Focus Area/Description
IEEE P3329 (DRAFT)	**Metrics & Benchmarking:** Establishes universal metrics for energy efficiency in quantum computing and simulation environments
IEEE P7130 (DRAFT)	**Terminologies and Concepts:** Establishes terminology and definitions to ensure clarity and interoperability across quantum domains
IEEE P7131 (DRAFT)	**Metrics & Benchmarking:** Standardizes performance metrics for quantum computing hardware and software, supporting consistent benchmarking
ISO TS 80004-12	**Terminologies and Concepts:** Lists terms relevant to quantum phenomena in nanotechnologies for cross-sector clarity
ISO/IEC DIS 4879	**Terminologies and Concepts:** Specifies common terms in quantum computing to support shared understanding and communication

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Standard Category — Materials Standards:
Efficiency; Characterization

Prominent Standard	Focus Area/Description
IEC 62607	**Quantum Efficiency:** Describes the procedures to be followed and precautions to be observed when performing reproducible measurements of the quantum efficiency of luminescent nanomaterials
ISO 20351 / JIS R1697	**Quantum Efficiency:** Describes a method of absolute measurement (using an integrating sphere) of internal quantum efficiency of phosphor powders
ISO TS 17466	**Materials Characterization:** Provides guidelines for estimating size and concentration of colloidal quantum dots
SAC GB/T 24370	**Materials Characterization: Defines UV-visible spectroscopy methods for characterizing CdSe quantum dot nanocrystals**

Standard Category — Quantum Computing Standards:
Hardware/software architectures; Hybrid systems; Algorithms; Datasets

Prominent Standard	Focus Area/Description
IEEE P2995 (DRAFT)	**Algorithm Design:** Provides a standardized method for designing quantum algorithms, supporting foundational software development
IEEE P3120 (DRAFT)	**System Architecture:** Defines technical architectures for quantum computers based on qubit modalities and technology types
System Architecture	**System Architecture:** Defines hardware and software architecture for hybrid quantum-classical systems foundational for interoperability
ISO/IEC PWI 18660	**Machine Learning Datasets:** Establishes benchmarks and dataset standards for quantum machine learning (QML) applications

Standard Category — Quantum Computing Standards:
Simulator architecture; Programming

Prominent Standard	Focus Area/Description
IEEE P3155	**Simulation Programming:** Programming methods for analog, digital, and hybrid quantum simulators
ISO/IEC PWI 20153	**Simulator Architectures:** Taxonomy of quantum simulator architectures and programming

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RELEVANT ROADMAPS AND STRATEGY DOCUMENTS

This section summarizes key national and international roadmaps, strategic plans, and policy frameworks that influence quantum standardization. These documents articulate long-term priorities, identify gaps, and guide coordinated action across government, industry, and academia. Four major strategy documents are included, each offering insights into all aspects of quantum computing, quantum sensing, quantum key distribution, and more.

1

2024 QUANTUM INFORMATION SCIENCE (QIS) APPLICATIONS ROADMAP [176]

U.S. Department of Energy
December 2024

Focus
This roadmap was produced by a DOE committee of experts from academia, national labs, and industry for applications within quantum information science. The committee concluded that QIS is a vibrant field with significant progress and promise capable of rivaling the impact of transistors and microprocessors. The roadmap outlines QIS in three areas: quantum computing, quantum sensing, and quantum networking.

DOE quantum research centers and testbeds: DOE established five National Quantum Information Science Research Centers and multiple testbeds

Application-driven focus: Roadmap organized around quantum computing, sensing, and networking

Interdisciplinary focus: Emphasizes the need for collaborative efforts across quantum science, classical engineering, materials science, and systems integration

Pre-standardization needs: Not explicitly a “standards” roadmap but identifies potential pre-standardization activities:

- **Benchmarking and performance metrics** across platforms
- **Interoperability and modularity** in quantum computing architectures
- **Robustness and reproducibility** in sensing platforms
- **Network architecture and protocol development** for quantum networks

Gaps
- **Absence of standardized quantum interconnects and modular architectures** as needed for scalable quantum computing
- **Hardware fragility and noise in quantum computing systems,** affecting device reliability, reproducibility, and performance metrics
- **Insufficient integration between quantum and classical systems;** may point to need for hybrid system standards
- **Lack of scalable quantum control systems** as related to interface and protocol standards

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- **Lack of scalable quantum networking protocols and infrastructure;** highlights absence of network architecture standards, protocol stacks, and performance benchmarks
- **Limited robustness of quantum sensors in extreme environments;** may implicate certification and performance standards

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2

EUROPEAN QUANTUM INDUSTRY CONSORTIUM (QUIC): STRATEGIC INDUSTRY ROADMAP (SIR) 2025[177]

QuIC, 2025

Focus

Outlines a pan-European vision through 2035 for development and industrialization of quantum technologies—particularly, quantum computing; emphasizes need for quantum-literate user community whose role is to translate use cases into executable quantum programs; includes inputs from 200+ QuiC members; aims to guide policymakers and industry leaders in building a robust, competitive, and sovereign European quantum ecosystem [178]

Gaps

- **Europe is vulnerable in quantum supply chains** and strategic dependencies [179]
- **Fragmented standardization and certification frameworks** across quantum domains [180]
- **Limited access** to scalable quantum hardware and cloud infrastructure within Europe [181]
- **Shortage of quantum-literate workforce** and interdisciplinary training pathways [182]
- **Underinvestment** in European quantum start-ups and scale-ups [183]

Opportunities

- Accelerating quantum advantage through hybrid quantum-classical integration [184]
- Building sovereign European quantum software infrastructure and APIs [185]
- Establishing European leadership in fault-tolerant quantum computing (FTQC) and quantum error correction QEC [186]
- Expanding quantum algorithm libraries and quantum-inspired solutions for industry [187]
- Industrialization of quantum sensing and metrology for high-impact applications [188]
- Leveraging photonic quantum computing for scalable, interconnected architectures [189]
- Positioning Europe as a global leader in quantum communications and cybersecurity [190]

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3

IEEE STANDARDIZATION ROADMAP ON QUANTUM APPLICATIONS [191]

IEEE, 2023

Focus

IEEE's quantum roadmap aims to link quantum technologies to real-world business problems by identifying application-ready use cases, technological limitations, and standardization needs across industries. The roadmap emphasizes aligning quantum development with stakeholder priorities—including investors, researchers, startups, regulators, and policymakers—by connecting business challenges to existing and emerging quantum technologies and standards. IEEE's roadmap intends to guide the evolution of quantum applications through a timeline-based framework that integrates technical readiness, market impact, and standardization pathways.

As of September 2025, the roadmap remains under development; the only publicly available document is the approved Industry Connections Activity Initiation Document (ICAID).

4

QUANTUM TECHNOLOGY MANUFACTURING ROADMAP [192]

SRI International/NIST, October 2023

Focus

This roadmap serves as the first industry-wide roadmap for quantum technology manufacturing across computing sensing, and telecommunications. It identifies 43 prioritized needs across 6 categories (materials and fabrication, electronics, lasers and optics, cryogenic and vacuum systems, control systems, testbeds); sets performance targets for 2024 and 2028; emphasizes the importance of scalable manufacturing, supply chain development, and pre-standardization infrastructure; and was developed through collaboration between quantum system developers and technology suppliers, coordinated by SRI International with support from NIST and QED-C.

Gaps

- **Diverse application needs complicate standardization and prioritization;** difficult to define university performance targets or manufacturing processes [193]
- **Fragmented industry with no dominant platform or standard configuration** which leads to diverse specifications and complicates supply chain alignment [194]
- **Insufficient domestic supply chains for critical components** like field programmable gate arrays (FPGAs), lasers, and cryogenic systems [195]
- **Lack of standardized specifications and shared data** across fabrication tools, cryogenic systems, and modeling platforms [196]
- **Limited workforce capacity, especially in quantum-aware hardware engineering** [197]
- **Low production volumes and uncertain market demand inhibit supplier investment** and delay scalable manufacturing solutions [198]
- **Tradeoffs between customization and cost;** off-the-shelf components are cheaper but less flexible, while custom tools are expensive and hard to scale [199]
- **Unclear incentives for developing quantum-specific tools and materials**, especially in areas like crystal growth and defect placement; little progress expected without government funding [200]
- **Underdeveloped testbed infrastructure and limited access** [201]

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Opportunities

- **Advance machine learning tools for materials discovery, defect engineering, and system modeling** [202]
- **Develop application-specific roadmaps** (e.g., for quantum computing, sensing, and networking) to better align manufacturing needs with use cases [203]
- **Develop technician-friendly systems and reskill complementary metal-oxide semiconductor (CMOS) engineers** to support quantum manufacturing workforce needs [204]
- **Encourage consolidation around common specifications and wavelengths** [205] to increase production volumes and reduce costs [206]
- **Expand international participation** to incorporate specialized expertise and broaden roadmap relevance [207]
- **Facilitate early collaboration between integrators and suppliers** to refine specifications and accelerate technology alignment [208]
- **Leverage existing semiconductor design tools** for quantum system modeling and integration [209]
- **Promote shared infrastructure and open-access testbeds,** especially white-box facilities [210] for experimental research and component validation
- **Support government-funded grand challenges and R&D programs to de-risk investment** in high-cost areas like photonic integration and crystal growth [211]

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⑤

STANDARDIZATION ROADMAP ON QUANTUM TECHNOLOGIES [212]

CEN/CENELEC, March 2023

Focus

This document resulted from the European Committee of Standardization (CEN) and the European Committee for Electrotechnical Standardizations (CENELEC) conducting 30 meetings involving over 200 different quantum experts. From these meetings, the group identified ongoing standardization activities, needs within quantum standardization, and opportunities. The report is designed to inform researchers and technical experts on opportunities to participate in standard development and how to receive public research grants through standardization bodies. The report comprises most quantum domains, including computing, sensing, and communication.

Gaps

- **Complexity of developing deployable quantum measurement standards:** Technical and reliability challenges in quantum metrology standardization
- **Fragmentation and uneven coverage across quantum domains**
- **Limited pool for quantum standardization expert**s
- **Limited standardization in quantum computing and sensing:** Current quantum related standards are on post-quantum cryptography, quantum key distribution, and quantum communication—quantum computing and sensing standards are comparably limited
- **Potential lack of standardized interfaces due to vertical integration:** Proprietary development may be inhibiting interface standardization
- **Varying readiness levels across quantum technologies**

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Recommendations
- **Avoid duplication and promote harmonization** to align European efforts with international standards bodies including ISO, IEC, ITU, and ETSI to ensure coherence and avoid fragmentation
- **Create European standardization roadmap for quantum technologies** to provide structured framework for identifying standardization needs and coordinating efforts across Europe
- **Develop standardized quantum terminology** to reduce confusion, enable fair comparison, and support cross-sector collaboration using CEN Workshop Agreements as a proposed mechanism to address this
- **Encourage participation from researchers and grant recipients** to engage with standardization bodies to ensure innovations are market-ready
- **Foster interaction between European Quantum Flagship and standardization bodies** to ensure research outputs are aligned with standardization priorities
- **Use CEN CWAs for early-stage standardization** in areas not yet ready for formal standards

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6

STATE OF QUANTUM COMPUTING: BUILDING A QUANTUM ECONOMY [213]

World Economic Forum, September 2022

Focus
This report provides a comprehensive overview of the quantum computing ecosystem, including its technological maturity, application domains, investment trends, and enabling infrastructure; emphasizes quantum computing's potential to transform industries including materials science, energy, agriculture, healthcare, finance, logistics, and cybersecurity; and highlights the need for workforce development, policy frameworks, and standardization to support responsible and scalable quantum innovation. The report is intended to guide business leaders, policymakers, and researchers in preparing for quantum readiness and shaping strategic responses to quantum disruption.

Gaps
- **Absence of scalable, fault-tolerant quantum hardware** capable of demonstrating quantum advantage in real-world applications [214]
- **Insufficient policy coverage** for energy efficiency, ethical development, and socioeconomic impacts of quantum computing [215]
- **Lack of coordinated international strategy for quantum computing;** fragmented global development pathways [216]
- **Lack of standardized benchmarks and performance metrics** for comparing quantum hardware and algorithms [217]
- **Limited interoperability across quantum platforms and premature standardization risks** due to divergent hardware architectures [218]
- **Quantum skills shortage across technical and non-technical roles,** with limited educational pipelines and industry-academia collaboration [219]
- **Vulnerability of current cryptographic systems to future quantum attacks;** slow adoption of quantum-resistant security measures [220]

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Opportunities

- Accelerated discovery in materials, energy, agriculture, and healthcare [221]
- Cloud-based access democratizing experimentation and early adoption [222]
- Cybersecurity innovation through quantum-safe cryptography [223]
- Development of performance benchmarks and common terminology [224]
- Early strategic engagement by industry can secure competitive advantage as quantum computing matures [225]
- Global public-private partnerships and pre-competitive collaboration [226]
- Optimization of complex systems in finance, logistics, and product design [227]
- Quantum-enhanced artificial intelligence and machine learning [228]

OTHER DOCUMENTS

The following roadmaps and strategy documents do not mention quantum standardization specifically and were not developed by SDOs. However, these roadmaps are relevant to the overall field of quantum technology and present some information relevant to standardization.

1

GOOGLE QUANTUM AI ROADMAP

Google, 2025

Focus

Focuses on building a large-scale quantum computer capable of performing "complex, error-corrected computations;" the roadmap outlines six major milestones, beginning with quantum advantage and culminating in a fully error-corrected quantum computer; it emphasizes breakthroughs in surface code error correction, scalable qubit architectures, and cryogenic control systems

Google's roadmap does not explicitly reference quantum standards but emphasizes potentially relevant topics on error correction fidelity, modular scaling, and benchmarking against classical systems

2

IBM QUANTUM 2025 DEVELOPMENT & INNOVATION ROADMAP [229]

IBM, 2025

Focus

Outlines a strategy to scale quantum computing from noisy intermediate-scale systems to fault-tolerant, utility-scale quantum-centric supercomputers by 2033; details milestones across hardware, software, orchestration, and innovation, and highlights modular processors, error correction, and AI-enhanced circuit transpilation; [230] also emphasizes transparent development and client-facing tools to support quantum utility and workload scaling

The roadmap does not explicitly refer to quantum standards but does mention tools and methods that support benchmarking and performance evaluation—such as "use case benchmarking toolkits" and "mapping and profiling tools for quantum + HPC workflows"

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Milestones
- **2024–2026:** Modular scaling with Heron and Nighthawk processors; error mitigation tools; AI-enhanced transpilation
- **2027–2029:** Introduction of Starling, a fault-tolerant system capable of running 100 million gates on 200 logical qubits

2033
- Launch of Blue Jay, a quantum-centric supercomputer capable of executing 1 billion gates on 2,000 logical qubits

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3

MICROSOFT QUANTUM ROADMAP [231, 232]
Microsoft, 2024

Focus
Microsoft's quantum roadmap outlines a staged approach to building a fault-tolerant, utility-scale quantum computer; outlines three "quantum computing implementation levels": foundational, resilient, and scale. The roadmap also emphasizes the development of topological qubits, quantum error correction, and scalable quantum hardware

While the roadmap does not explicitly refer to quantum standards, Microsoft acknowledges the importance of cryptographic standardization in the quantum era, noting that "post-quantum public key algorithms [are] currently undergoing standardization by NIST and other standardization bodies globally"

Gaps and Emerging Needs

This section identifies areas where quantum standards are lacking, insufficient, or fragmented. Due to quantum technology still being immature, **there are gaps and needs in most areas of quantum standardization,** including: quantum communication, quantum computing, quantum simulation systems, quantum internet, quantum metrology, quantum sensing, and quantum imaging. Gaps were identified through analysis of government reports, roadmaps for quantum technologies and standards, and academic research.

AREAS LACKING STANDARDS

Absence of security certification frameworks for quantum communication networks [233, 234]
Quantum communication systems—especially those using QKD—currently lack comprehensive and broadly accepted security certification frameworks. ETSI released the first Protection Profile for QKD modules in 2023 as an initial step to close this gap. CEN-CENELEC has noted that foundational standards necessary for certifying QKD systems remain incomplete or insufficient. These gaps limit the ability to evaluate and assure the security of quantum communication technologies in a standardized, internationally recognized manner.

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Inconsistent benchmarking and performance metrics across quantum systems [235, 236, 237]

Quantum computing platforms currently rely on proprietary or informal benchmarks that lack consistency, transparency, and cross-platform comparability. This gap limits the ability to evaluate system capabilities, track progress, and make informed decisions. There are currently efforts by IEEE (e.g., P7131) and QED-C to define performance metrics and benchmarking frameworks, but formal standards remain fragmented and are not yet widely adopted across the quantum ecosystem.

Insufficient cryptographic and security standards for quantum communications [238, 239, 240]

Quantum communications systems including those using QKD lack comprehensive, harmonized standards for security evaluation and integration with classical cryptographic frameworks. ETSI Industry Specification Group on Quantum Key Distribution (ISG-QKD) and ISO/IEC SC27 WG3 are developing Common Criteria Protection Profiles and test methodologies for QKD; foundational standards remain incomplete and fragmented. ISO/IEC SC27 WG3 is advancing QKD security standards through ISO/IEC 23837-1 and -2 which define security functional requirements and evaluation methods for QKD modules. NIST is coordinating the transition to PQC and has acknowledged that application-specific security protocols remain underdeveloped. [241]

Lack of application-specific standards for emerging quantum domains [242, 243, 244]

Quantum technologies for simulation, sensing, and photonics lack tailored standards defining performance, characterization, and integration requirements for specific use cases. This prevents the ability to properly certify components, compare systems, and ensure interoperability across different industry sectors (e.g., defense, healthcare, advanced manufacturing). ETSI, ISO/IEC, and the European FGQT (CEN-CENELEC Focus Group on Quantum Technologies) have proposed technical specifications for quantum devices like clocks and magnetometers. Further coordination is needed between standards bodies and experts representing specific industries or application areas.

Limited interoperability standards across quantum platforms and components [245, 246, 247]

Quantum systems lack standardized interfaces that enable seamless integration across hardware platforms, software stacks, and networked components. This lack of interoperability precludes scalability, compatibility across vendors, and coordinated development of quantum technologies. ETSI, ITU-T, ISO/IEC, and IEEE have all initiated efforts to define architectures and integration frameworks including QKD networks and computing stacks. Formal interoperability standards remain underdeveloped or drafted, or not yet widely adopted.

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Missing component-level standards for quantum photonic devices[248,249]
Single-photon sources, detectors, modulars, and other quantum photonic devices lack widely adopted standards needed for performance characterization, interoperability, and certification. This prevents the ability to compare devices across vendors and hinders integration into larger quantum systems. ETSI has published a specification for characterizing optical components in QKD systems. CEN-CENELEC's FGQT has acknowledged that many foundational standards remain incomplete or insufficient.

No formal standards for quantum software stack interoperability[250,251,252,253]
The quantum software ecosystem is fragmented; the lack of formal interoperability standards comes from the field's rapid evolution and diversity of hardware architectures. Many software tools, including programming languages and compilers, are developed in isolated by different vendors, resulting in limited compatibility across platforms. This slows the development of hybrid and scalable quantum computing systems and can limit the portability of quantum programs. Initiatives like QED-C's Practical Intermediate Representation for Quantum (PIRQ) and Microsoft's Quantum Intermediate Representation (QIR) Alliance are beginning to address these challenges, but it is currently unclear if their outputs have yet been formalized through recognized SDOs.

GENERAL/CROSS-CUTTING CHALLENGES

Difficult to scale quantum repeaters due to immaturity of quantum memory technologies
Quantum repeaters remain difficult to scale due to immature quantum memory technologies and lack of performance standards, thereby restricting the development of long-distance quantum communication networks.[254,255]

Fragmented component supply chains and lack of interface compatibility
Quantum hardware development is constrained by fragmented supply chains and proprietary interfaces, which limit interoperability and scalability. Without standardized components and materials, the quantum ecosystem faces persistent risks of disruption and bottlenecks associated with the integration of quantum technologies.[256,257]

Fragmented global governance and inconsistent coordination across quantum standards efforts
National strategies and regional priorities often diverge, leading to misalignment in international standardization activities. This complicates efforts to harmonize terminology, performance metrics, and interoperability across quantum domains.[258,259]

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Frameworks for responsible innovation and governance in quantum technologies are nascent or early-stage

Ethical, societal, and security considerations are often absent from quantum governance strategies, creating gaps in trust and accountability. Structured frameworks help reduce the implementation risk with respect to deploying quantum technologies. [260, 261]

High infrastructure costs limit accessibility and slow ecosystem expansion

Quantum computers require highly specialized infrastructure, including cryogenic cooling systems, ultra-low-noise environments, and precision control electronics; this can drive up costs and limit access to a small number of well-funded institutions. These capital-intensive requirements pose barriers to broader participation in quantum R&D, particularly for startups, academic institutions, smaller enterprises, and emerging economies. Costs are expected to decline as quantum technologies mature, but current R&D and deployment remain capital-intensive, which slows broader ecosystem growth. [262, 263]

Lack of validated performance models for quantum sensing and metrology devices

Quantum sensing and metrology devices lack validated performance models, making it difficult to assess reliability, reproducibility, and integration readiness; this also inhibits the development of certification frameworks and slows deployment in critical applications. [264, 265]

Low expected financial return for quantum vendors

While quantum computing could generate $877 billion by 2035, quantum vendors are only expected to accumulate about 6% of that total. This contradicts most emerging technologies where traditionally those involved early see the most significant returns. Value generated will mostly go towards companies implementing the technology, such as life sciences companies or financial institutions. Further, Quantum Computing as a Service (QCaaS) is gaining momentum. Smaller companies creating quantum computers will realize less of the benefit if they cannot offer this capability, as large companies like Amazon and Google may dominate. The high capital costs and long R&D timelines to create quantum technology may make quantum less viable as a business. [266]

Low industry awareness and limited participation in formal standards development [267, 268, 269]

Many quantum startups and researchers are unfamiliar with formal standards processes, resulting in underrepresentation and missed opportunities for shaping standards. The National Quantum Coordination Office has noted that engaging the private sector remains a key challenge because many companies are still navigating the complexities of commercialization, governance, and global coordination in quantum technologies.

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Mismatch between the pace of quantum innovation and the speed of standards development
Quantum technologies are advancing rapidly, but many remain in early-stage development, making it difficult to establish robust standards without risking premature lock-in. Some applications, such as quantum sensing for navigation, have reached pilot deployment, but most use cases are still theoretical or limited to research environments. The gap between innovation and standardization timelines complicates efforts to define interoperability, performance benchmarks, and certification frameworks. [270, 271, 272]

Need for modular benchmarking frameworks across quantum computing platforms
The absence of modular, application-oriented benchmarking frameworks limits the ability to compare quantum computing platforms and assess performance consistently. Standardized benchmarking tools are needed to support reproducibility, guide technology selection, and enable meaningful evaluations across platforms. [273, 274]

Persistent skills and workforce gaps in quantum standardization expertise
The quantum workforce pipeline remains underdeveloped, and there is limited access to interdisciplinary training and hands-on experience in quantum information science and engineering (QISE). Some institutions have launched graduate programs in quantum engineering, but fewer than 20 universities globally offer dedicated quantum computing degrees, leaving few structured pathways for students to enter the field. Quantum education requires proficiency across physics, computer science, mathematics, and engineering, yet undergraduate exposure remains minimal. National initiatives such as NSF's Quantum Leap Challenge Institutes and the QED-C's experiential learning roadmap emphasize the need for mentorship, early engagement, and practical training to bridge the gap between academic instruction and industry needs—especially in areas like quantum software engineering, hardware integration, and standards literacy.[275, 276, 277]

GAPS REQUIRING PRE-STANDARDIZATION R&D

Insufficient deployment experience limits standards readiness [278, 279]
Due to the immaturity of quantum technologies and lack of resources and infrastructure, many applications remain theoretical and have not been enacted in real-world environments. Because standards development requires operational experience with these technologies. the ability to produce standards, particularly domain-specific standards like in finance or healthcare, are limited.

Lack of dominant design hinders quantum computer standardization [280, 281, 282, 283]
Quantum computer developers continue to pursue diverse hardware modalities—including superconducting qubits, trapped ions, photonic systems, and neutral

atoms—each with distinct approaches to encoding, manipulating, and reading quantum information. While these modalities offer similar core functionality (e.g., gate-based or measurement-based operations), they differ significantly in fidelity, speed, connectivity, and error sources. For example, superconducting qubits used by IBM and Google enable fast gate operations, whereas trapped ion systems offer high coherence and all-to-all connectivity. This diversity in design and control systems means that standardization must either accommodate multiple architectures or wait until a dominant design emerges.

Lack of validated taxonomies and reference architectures for quantum computing and simulation platforms

The diversity of quantum computing modalities—including superconducting, trapped ion, and photonic systems—has led to fragmented design approaches without a unified framework for classification or architecture. Advancing consensus on reference architectures and taxonomies can enable interoperability, benchmarking, and scalable system integration. [284, 285]

Materials and fabrication limitations hinder reproducibility and scalability

The performance and scalability of quantum technologies are constrained by fabrication challenges and material imperfections. Current chip fabrication techniques often rely on organic materials that introduce defects (e.g., two-level systems) that degrade qubit fidelity and are difficult to detect or eliminate. While new materials and cleaner fabrication processes could improve reproducibility, these approaches need further R&D and standardization. [286] Further, the use of rare earth elements and other critical materials raises concerns about supply chain resilience, particularly for countries lacking domestic resources. [287]

Need for foundational measurement science and metrology for quantum systems

Quantum systems require precise and reproducible measurement techniques to support future standards, yet foundational metrology frameworks remain pre-mature or underdeveloped. Pre-standardization R&D is needed to establish reproducible methods for sensing, benchmarking, and characterizing quantum systems across modalities. Addressing this is expected to improve consistency in performance comparison and certification efforts. [288, 289, 290]

No consensus on datasets and evaluation protocols for quantum machine learning

QML currently lacks standardized datasets and evaluation protocols, which hinders consistent benchmarking, cross-platform testing, and reproducibility of algorithmic performance. As QML applications expand, pre-standardization R&D is needed to define representative datasets and develop evaluation frameworks that reflect the hybrid nature of quantum-classical systems. [291, 292, 293]

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Scalability and power management challenges complicate system integration [294, 295, 296, 297]

Scaling quantum systems requires the integration of large numbers of qubits while maintaining fidelity, coherence, and control. Each qubit introduces noise and error sources and connecting them across chips or modules adds complexity. With respect to power management issues, quantum systems demand precise energy control and isolation from environmental interference. These challenges, combined with the cost of scaling infrastructure, limit the feasibility of large-scale, fault-tolerant quantum computers in the near term.

Ongoing and Emerging Standardization Efforts

This section highlights current initiatives, working groups, and collaborative programs that are actively shaping the quantum standards landscape; it includes efforts led by formal SDOs, industry consortia, and public-private partnerships focused on areas such as benchmarking, interoperability, security, and component validation. The section also captures pre-standardization activities—such as testbed development, reference architectures, and reproducibility protocols—that signal emerging priorities and lay the groundwork for future formal standards. These efforts reflect the dynamic and rapidly evolving nature of quantum technology development and the growing momentum toward scalable and trustworthy quantum systems.

ACTIVE WORKING GROUPS

CEN-CENELEC JTC 22

CEN-CENELEC JTC 22 was formed in 2022 by the CENELEC FGQT to develop standards across quantum computing, communications, sensing, and enabling technologies. [298] The Committee operates through four working groups, is aligned with other bodies, including ISO/IEC JTC 3 and ETSI, and supports EU policy goals including digital sovereignty and innovation. [299]

ETSI Industry Specification Group on Quantum Key Distribution (ISG QKD)

ETSI ISG QKD is a leading European industry specification group focused on developing standard for QKD and quantum cryptography since 2008, and includes stakeholders from equipment vendors, telecom operators, end users, national metrology institutes, and leading security researchers. The group has published specifications covering QKD interfaces, security proofs, REST (REpresentational State Transfer Application Programming Interface) APIs, and Software-Defined Networking (SDN) orchestration, and has an active role in ensuring interoperability and security in quantum communication networks. Their mission supports the global deployment of a QKD-based infrastructure. [300]

ETSI Technical Committee CYBER Working Group on Quantum-Safe Cryptography (ETSI TC WG QSC)

ETSI TC WG QSC develops specifications and migration frameworks for cryptographic systems resistant to quantum attacks. [301, 302] The group evaluates algorithm agility, performance, and security, and supports real-world deployment across diverse sectors. Key outputs include ETSI TR 103 619 and ETSI TR 104 016. [303, 304]

European Commission High-Level Forum – Workstream 16 [305, 306]

Workstream 16 was established within the European Commission's High-Level Forum on Standardization to provide a dedicated venue for political and technical dialogue on quantum technologies. It supports strategic coordination across European and international standards bodies—including CEN-CENELEC JTC 22 and ISO/IEC JTC 3—and ensures that quantum standardization reflects EU priorities such as digital sovereignty, industrial competitiveness, and trusted innovation.

International Organization for Standardization / International Electrotechnical Commission Joint Technical Committee (JTC 1) Working Group 14 (WG 14) [307, 308]

WG 14 focuses on quantum information technology standardization and develops foundational standards for terminology, architecture, simulation, and quantum machine learning datasets. WG 14 includes 23 national bodies and over 150 subject matter expert (SME) members and serves as a key contributor to the global quantum standards ecosystem.

International Organization for Standardization / International Electrotechnical Commission Joint Technical Committee 3 (JTC 3)

JTC 3 focuses on standardization for quantum computing, simulation, communication, metrology, sources, and detectors. It is chaired by South Korea and administered by the British Standards Institution (BSI). April 2026, JTC 3 operates through eight Working Groups and two Project Teams, reflecting its transition from earlier exploratory structures to formalized working bodies. The committee aims to unify international efforts and accelerate the adoption of quantum technologies through interoperable, secure, and globally accessible standards.[309, 310] JTC 3 was established following recommendations from IEC Systems Evaluation Group (SEG) 14 and a joint decision by ISO and IEC to consolidate quantum standardization under a single governance structure. [311]

National Quantum Coordination Office (NQCO) [312, 313, 314]

The NQCO is located within the White House Office of Science and Technology Policy (OSTP) and is tasked with overseeing the U.S. National Quantum Initiative (NQI). NQCO facilitates interagency collaboration with NIST, DOE, NSF, and DoD, and co-chairs interagency working groups. NQCO provides technical and administrative support to the National Science and Technology Council (NSTC) Subcommittees on Quantum Information Science (SCQIS) and the Economic and Security Implications of Quantum Science (ESIX). NQCO claims to serve as a central point of contact for federal quantum activities. They also conduct public outreach and promote early access to and application of quantum technologies.

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NQCO plays a coordinating role for the DOE National QIS Research Centers (5 centers) and NSF Quantum Leap Challenge Institutes (five institutes).

National Institute of Standards and Technology [315, 316]
NIST leads multiple quantum standards efforts through internal working groups focused on quantum measurement, benchmarking, and post-quantum cryptography. Through its Communications Technology Laboratory (CTL), NIST develops reference architectures for quantum routing and hybrid quantum-classical networks; its Quantum Measurement Division advances quantum metrology by developing measurement tools that exploit quantum behavior. NIST created the BenchQC toolkit for benchmarking algorithm performance. NIST also coordinates with the U.S. Technical Advisory Group to ISO/IEC JTC 3 on international quantum standards contributions and supports pre-standardization efforts through the QED-C. NIST also finalized the first three post-quantum cryptography standards—now ready for immediate adoption—to help secure digital communications against quantum attacks.

ACTIVE STANDARDS INITIATIVES

ATIS Quantum-Safe Communication and Information Initiative (QSCII) [317, 318, 319]
QSCII is led by the Alliance for Telecommunications Industry Solutions (ATIS) and is focused on preparing North American telecom infrastructure for quantum threats by developing migration strategies, interoperability framework, and cryptographic agility tools. ATIS published technical guidance on integrating quantum-resistant cryptography into 5G architecture. The initiative introduced a telecom-specific Cryptographic Bill of Materials (CBOM) to help operators inventory cryptographic assets and align with emerging quantum-safe standards.

EuroQCI (European Quantum Communication Infrastructure Initiative)
EuroQCI is a pan-European initiative that seeks to deploy a secure quantum communication infrastructure across 27 EU Member States. The initiative integrates terrestrial fiber networks and satellite systems to enable quantum-safe communications for government institutions, hospitals, energy grids, and critical infrastructure. EuroQCI contributes to quantum standards by funding testing and evaluation infrastructure for QKD devices, protocols, and architectures. The initiative has a total budget €90 million and received 24 proposals from 15 countries [320, 321, 322, 323]

Horizon 2020 OPENQKD Project [324, 325]
OPENQKD is funded under the EU's Horizon 2020 program which aims to establish a robust experimentation platform for QKD across Europe, involving 38 organizations to demonstrate use cases in telecom, data security, and critical infrastructure. OPENQKD contributes to standards development by identifying gaps in QKD component interoperability, certification, and network integration. They also directly support the ETSI Industry Specification Group on Quantum Key Distribution

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(ISG QKD). OPENQKD proposed a roadmap to prioritize standards development activities which identifies urgent gaps in quantum security, interoperability, and component certification, and recommends short-term support for QKD components, medium-term development of standards for advanced protocols and quantum repeaters, and coordinated efforts for fiber and satellite QKD interoperability to enable a future quantum internet. [326]

IEEE Quantum Initiative [327, 328, 329]

The IEEE Quantum Technical Community (QTC) serves as the central organizing body for IEEE's quantum-related activities, including standards development, education, and interdisciplinary collaboration. QTC leads over a dozen active quantum standards projects including efforts on terminology (P7130), benchmarking (P7131), hybrid quantum-classical architectures (P3185), and post-quantum cryptography migration (P3172). IEEE fosters cross-sector engagement through working groups, technical papers, and community events like IEEE Quantum Week that support both formal standards and pre-standardization collaboration. IEEE's standards development process enables early-stage consensus building while preparing for scalable deployment.

National Quantum Initiative (NQI) [330]

The National Quantum Initiative (NQI) was established by the National Quantum Initiative Act of 2018 and is responsible for coordinating federal quantum research and standards development across NIST, NSF, DOE, DoD, NASA, National Security Agency (NSA), and Intelligence Advanced Research Projects Activity (IARPA). NQI supports a 10-year strategy to accelerate quantum R&D, promote interagency collaboration, and guide commercialization and workforce development. NQI activities include the creation of quantum research centers, stakeholder consortia, and advisory bodies that contribute to standards-relevant outputs in quantum computing, sensing, and communications. As of 2024, NQI has supported more than 2,000 quantum R&D grants, engaged 23 agencies, and established 14 major research centers and institutes across 47 states. [331] The National Quantum Initiative (NQI) is being expanded and extended through 2034 via the bipartisan National Quantum Initiative Reauthorization Act of 2026, introduced in January 2026 to succeed the original 2018 act. This new phase shifts focus from basic research to practical application, authorizing new quantum centers at NIST and NSF, including NASA in R&D, and strengthening supply chains. [332]

NIST's quantum research program [333]

NIST plays a central role in advanced quantum standards through its leadership in measurement science, benchmarking, and international coordination. NIST was selected by ANSI to administer the U.S. Technical Advisory Group to the ISO/IEC Joint Technical Committee on Quantum Technologies (JTC 3), which serves as the global hub for quantum standardization. Their contributions span pre-

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standardization efforts in quantum photonics, sensors, and enabling technologies, and include the development of deployable standards for post-quantum cryptography, timekeeping, and quantum networking. NIST also maintains quantum network testbeds, supports the QED-C, and collaborates with DOE, NSF, and DoD through joint research centers and consortia. NIST is positioned as a foundational institution in shaping the technical infrastructure and governance of the U.S. quantum ecosystem.

DRAFT STANDARDS

Standards Development Organization — IEEE

Draft Standard	Focus Area/Description
P7130 [334]	**Terminologies and Concepts:** Standard for Quantum Technologies Definitions
P7131 [335]	**Metrics & Benchmarking:** Standard for Quantum Computing Performance Metrics & Performance Benchmarking
P3329 [336]	**Metrics & Benchmarking:** Standard for Quantum Computing and Simulation Energy Efficiency
P1913 [337]	**Network Architecture:** Software-Defined Quantum Communication
P1943 [338]	**Security:** Standard for Post-Quantum Network Security
P3172 [339]	**Cryptography:** Recommended Practice for Post-Quantum Cryptography Migration
P3120 [340]	**System Architecture:** Standard for Quantum Computing Architecture
P3185 [341]	**System Architecture:** Standard for Hybrid Quantum-Classical Computing
P2995 [342]	**Algorithm Design:** Trial-Use Standard for a Quantum Algorithm Design and Development

Standards Development Organization — ISO/IEC

Draft Standard	Focus Area/Description
AWI TR 18157 [343]	**Foundational Concepts:** Information technology – Introduction to quantum computing
PWI 18670 [344, 345]	**System Architecture:** General requirements for quantum resource simulation platform; Reference framework for quantum computing service platforms
PWI 18660 [346, 347]	**Datasets & Machine Learning:** Information technology — Quantum machine learning datasets
PWI 20153 [348]	**Quantum Simulation:** Quantum Simulation - Taxonomy of quantum simulator architectures and quantum simulation programming

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Standards Dev elopment Organization — NIST

Draft Standard	Focus Area/Description
NIST HQC algorithm (due 2026) [349]	**Cryptography:** Backup Algorithm for Post-Quantum Encryption
NIST FN-DSA (Future FIPS 206) [350]	**Cryptography:** Floating-Point Digital Signature Algorithm (FN-DSA)

NATIONAL AND INTERNATIONAL STRATEGIES

Governments and international bodies are increasingly recognizing the strategic importance of quantum technologies and the need for coordinated standards development. The strategies outlined below reflect a mix of national priorities, economic ambitions, and technical roadmaps that aim to position countries as leaders in the quantum ecosystem. These documents guide public investment and research agendas and influence the pace and direction of standards-setting activities—particularly in areas such as benchmarking, interoperability, and security. These strategies can offer insight into how different regions are shaping the global quantum landscape and identifying opportunities for alignment and collaboration.

UNITED STATES

National Quantum Initiative

The National Quantum Initiative is a whole-of-government approach to ensure the continued leadership of the United States in quantum information science and its technology applications. Established in 2018 by the National Quantum Initiative Act, the NQI coordinates quantum R&D across civilian, defense, and intelligence agencies. The initiative engages several agencies including NIST, NSF, DOE, NASA, and DoD, and has been expanded through the CHIPS and Science Act to include quantum networking infrastructure, standards development, and access to quantum computing centers. [351, 352]

DOE National Quantum Information Science (QIS) Research Centers [353, 354]

Five DOE National QIS Research Centers—Co-design Center for Quantum Advantage (C2QA), Q-NEXT, QSC, Quantum Systems Accelerator (QSA), and Superconducting Quantum Materials and Systems Center (SQMS)—were established in 2020 as collaborative hubs led by the DOE national labs. The research centers involve over 1,500 experts across 115 institutions research centers, and seek to advance quantum computing, communication, sensing, and materials science. Their work spans foundational research and technology development including quantum deice fabrication, testbeds, and workforce training.

- **Q-NEXT quantum foundries and database:** Q-NEXT launched two national quantum foundries and is working to establish a National Quantum Devices Database toward standardizing quantum components and enabling reproducibility.

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CHIPS Tech Hubs [355, 356, 357, 358]

The CHIPS and Science Act established the Tech Hubs Program to accelerate regional innovation in critical and emerging technologies. There are 31 designated Tech Hubs, including two hubs focused on quantum technologies: the Bloch Tech Hub and Elevate Quantum Colorado.

The CHIPS and Science Act authorizes implementation grants ranging from $22M to $75M, depending on project scope and alignment with national competitiveness goals. Tech Hubs are eligible to compete for implementation grants; funding levels are determined based on the scope and maturity of proposed projects, including infrastructure, workforce development, and technology advancement, and are intended to support regional innovation aligned with the program's goals of enhancing U.S. competitiveness and national security.

- **Elevate Quantum:** [359, 360, 361] Elevate Quantum received a $41M Phase 2 Implementation award from the Economic Development Administration (EDA) and subsequently unlocked more than $127M in combined federal and state funding; they are eligible for up to $1B in potential future federal investment. Elevate Quantum is developing the Quantum Commons in Mountain West, a 70-acre campus that will house shared labs, photonic integrated circuit (PIC) fabrication facilities, and flexible office space to support startups and scale-ups. Elevate Quantum is focused on three key areas: 1) creating tools for rapid prototyping of all quantum technologies, 2) ensuring an educated and sustainable quantum-led workforce, and 3) investing in accelerator programs to move entrepreneurs into the field faster. These shared-used facilities are designed to enable reproducibility, benchmarking, and access to quantum hardware, which are foundational to pre-standardization activities in quantum technologies. The initiative aims to create 10K+ quantum jobs and educate 30K workers by 2030.

- **Bloch Tech Hub:** [362, 363] The Bloch Tech Hub is based in Chicago, Il and is led by the Chicago Quantum Exchange; they aim to position the region as a global leader in quantum computing and quantum communications by leveraging its strengths in research universities, national laboratories, and industry partners. Their strategy includes:

  1. Creating a publicly usable commercial-grade quantum network testbed to support QKD and long-distance quantum communication
  2. Developing a framework for industry adoption of quantum technologies
  3. Building and innovation-focused office and lab space to support startups and scale-ups in quantum information science and technology (QIST)
  4. Fostering regional collaboration to accelerate commercialization and workforce development

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These activities are designed to advanced U.S. national security and global competitiveness in quantum technologies. While the sources do not explicitly reference pre-standardization activities, potential pre-standardization activities to be considered include those that enable component-level testing, reproducibility, and cross-platform integration.

NSF Quantum Leap Challenge Institutes [364, 365]
Established by NSF, the Quantum Leap Challenge Institutes (QLCI) are large-scale, interdisciplinary research projects solving problems at the forefront of quantum information science and technology. The QLCI are designed to catalyze breakthroughs in quantum computing, communication, simulation, and sensing. They also serve as hubs for education, workforce development, and industry engagement, and are aligned with the goal of the National Quantum Initiative. Each QLCI supports multi-institutional teams working on application-driven quantum research, and several institutes contribute to pre-standardization efforts by developing testbeds, benchmarking protocols, and reproducible quantum platforms that can inform future quantum standards.

Center of Excellence in Advanced Quantum Sensing at Delaware State University (DSU) [366,367, 368]
The Advanced Quantum Sensing (AQS) Center was launched in 2021 as a U.S. Department of Defense institution through a $7.5 million DoD grant. The center conducts cutting-edge research in quantum sensing to enhance position, navigation, and timing capabilities for defense applications. The Center collaborates with other institutions like Northwestern University, Army Research Laboratory (ARL), Naval Research Laboratory (NRL), and Harvard to contribute to research projects on ultra-precise quantum sensors and experimentation on cold-atom-based systems and spin squeezing. The Center is not a formal standards development body but does contribute to pre-standardization by advancing experimental capabilities that may inform future metrology and performance benchmarks. It also prioritizes quantum information science education and workforce development by supporting undergraduate and graduate scholars through curriculum development, hands-on prototyping, and internships at defense laboratories to build a diverse and technically capable pipeline aligned with national quantum priorities.

EUROPE

European Quantum Flagship and Quantum Europe Strategy [369, 370, 371, 372, 373, 374]
The European Quantum Flagship was launched in 2018 with over €1 billion in funding as a major, 10-year EU initiative to advance quantum computing, simulation, communications, and sensing. It aims to position Europe as the global leader in quantum technologies through coordinated research, industrial engagement, and infrastructure development, and has a long-term vision of building a quantum internet—an interconnection of quantum computers, simulators, and sensors via quantum communication networks. While the Flagship drives technical

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progress, the Quantum Europe Strategy, adopted in 2025, provides a broader policy framework for scaling quantum technologies across Europe. The strategy complements the Flagship by addressing governance, infrastructure coordination, and workforce development. Standardization is a shared priority across both efforts, with initiatives to promote interoperability and reduce fragmentation across quantum systems. They are supported by major standards bodies including CEN-CENELEC JTC 22 and ISO/IEC JTC 3.

CANADA

National strategy and sustained public investment [375, 376, 377, 378, 379]
Canada's leadership in quantum can be attributed to its National Quantum Strategy (NQS) which provides $360M (CAD) in federal funding to support R&D, talent development, and technology commercialization. The NQS defines three missions: quantum computing, secure communications and post-quantum cryptography, and quantum sensing. Additional public funding has been allocated through the Natural Sciences and Engineering Research Council of Canada (NSERC) and the National Research Council of Canada (NRC) including $74M (CAD) for 107 quantum research projects. Canada's government cited a 2020 study by the NRC which estimates the Canadian quantum industry will deliver economic returns of $139B (CAD) and over 200,000 jobs by 2045. Since 2012, the Government of Canada has invested more than $1 billion in quantum science.

Quantum ecosystem; regional innovation hubs [380, 381, 382]
Canada's quantum ecosystems have three major regional clusters which host world-class institutions and startups working across photonic computing, quantum annealing, cryptography, and sensing:

1. **Toronto–Waterloo (IQC, Xanadu):** Focus on photonic quantum computing and quantum software; Xanadu leads fault-tolerant architectures and domestic supply chain development
2. **Vancouver (D-Wave, 1QBit):** Specializes in quantum annealing and hybrid algorithms; D-Wave commercializes annealing systems, 1QBit advances quantum chemistry and optimization
3. **Montreal–Sherbrooke (DistriQ):** Quebec's Quantum Innovation Zone; integrates startups and researchers to deploy quantum tech in energy, materials, and infrastructure

According to a 2023 report from the Council of Canadian Academies, Canada ranks second globally in the number of quantum SMEs, trailing only the United States. [383] Academic-industry collaborations, such as the Xanadu–NRC–University of Toronto battery simulation project, demonstrate Canada's ability to translate quantum research into real-world applications. [384]

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Active role in quantum standards, metrology [385, 386]
Canada is advancing quantum standards through the Standards Council of Canada (SCC) and collaborative efforts with NRC and NSERC. While CSA Group—a Canadian-based SDO and core partner of ASCET—is not a leader actor in quantum specific standards, they do contribute to adjacent areas such as cryptographic migration and ICT protocols that support quantum-safe infrastructure. [387]

International partnerships and quantum diplomacy
Canada is engaged in international quantum cooperation through joint initiatives with the United States (U.S. National Science Foundation) and France (ANR). [388, 389] Canada attended the 2025 G7 Summit where it prioritized quantum technologies as a strategic focus; the Summit resulted in the formation of the G7 Joint Working Group on Quantum Technologies. [390, 391] Canada also collaborates through the International Council of Quantum Industry Associations (ICQIA). [392]

Multi-sector industry adoption and commercialization of quantum technologies
Canada helps support scale-up efforts for quantum startups through programs like Innovative Solutions Canada (ISC) and Global Innovation Clusters. [393] Several Canadian companies, including Xanadu, D-Wave, and ISARA, are engaged in quantum topics including photonic computing, quantum annealing, and post-quantum cryptography. [394, 395, 396]

– **Canada's BOREALIS Initiative:** [397, 398] The BOREALIS (Bureau of Research, Engineering and Advanced Leadership in Innovation and Science) will coordinate federal investments in major frontier technologies including quantum, AI, and advanced materials. The initiative is backed by $2.4M (CAD) in funding as part of Canada's new defense and innovation strategy. BOREALIS is designed to accelerate commercialization, strengthen sovereignty, and position Canada as a global leader for "technologies shaping global security."

CHINA

Massive state-directed funding in quantum
China's government outpaces public spending in quantum R&D by any other nation, claiming over $15B of investments. Funding is directed through state-controlled labs, elite universities (e.g., University of Science and Technology of China [USTC]), and government-led industrial hubs like Quantum Avenue.

– **State-backed industrial clusters accelerate commercialization:** [399] Hefei's Quantum Avenue exemplifies China's strategy of co-locating research and manufacturing to create a direct pipeline from academic research to market-ready technologies.

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Focused strategy on quantum communications infrastructure
China leads the world in quantum communications; it built the largest terrestrial quantum network—12,000 km in length—and launched the first quantum satellite known as "Micius." [400] This has helped position China as the global frontrunner in QKD and secure communications.

China's efforts to shape international standards [401, 402]
China has elevated standards development to a national priority through its National Standardization Development Program (NSDP) as part of a broader effort to project geopolitical influence through leadership in next-generation technologies. The NSDP mandates that researchers and institutions integrate standards-setting into their project work. This centralized, state-controlled is intentionally designed to ensure Chinese technologies become the global benchmark to secure a strategic advantage over competitors like the United States.

China uses state control to integrate research, industry, and standardization efforts [403, 404, 405]
China's quantum ecosystem is centrally orchestrated; they exert control laboratories, elite universities (e.g., USTC), and private companies to form a vertically integrated pipeline from basic research to commercialization. Government-led hubs like Hefei's Quantum Avenue accelerate this process by co-locating R&D, manufacturing, and application development. This enables rapid deployment of quantum technologies aligned with national priorities.

China's state-control approach also embeds standards development into the innovation process to ensure China's technological advances are accompanied by domestic standards that can be leveraged in international forums.

FRANCE

National strategy and quantum funding [406, 407, 408, 409]
France launched its National Quantum Strategy in 2021 which commits €1.8 billion to accelerated quantum R&D, commercialization, and workforce development.

Their strategy sets goals to:
1. build fault-tolerant quantum computers
2. advance quantum sensing and communications
3. train 5,000 quantum professionals at various levels (from technician to PhDs)

Research and innovation ecosystem [410, 411, 412, 413, 414]
France's major institutions contributing to quantum research include CEA, CNRS, INRIA, and several universities.

- **Major quantum start-up companies:** Prominent start-up companies in France have attracted government support and at least €100M in private investments

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to develop fault-tolerant quantum systems; they include Alice & Bob, Pasqal, Quandela, and Qobly.

- **France's research pillar:** [415] A research pillar of France's strategy is the Quantum Priority Research and Equipment Program (PEPR Quantum). PEPR is a €150M program led by CEA, CNRS, and INRIA that supports academic research from fundamental science to proof of concept and is responsible for coordinating efforts across major institutions to accelerate breakthrough concepts toward industrial deployment. Targeted projects of France's PEPR are based on four strategic research domains: solid-state qubits, cold-atom qubits, quantum algorithms, and quantum communication.

Active role in standards development [416, 417, 418]

France has a national program called MetriQs-France which is focused on quantum measurement, benchmarking, and standardization. The program is coordinated by LNE, CNRS, and AFNOR (France's national standards body) and includes the BACQ project (Benchmarks for Application-Centric Quantum Computing) which is dedicated to application-oriented benchmarks for quantum computing (i.e., evaluation tools for quantum systems). LNE also announced a major metrology breakthrough in 2025: a new electric current quantum standard that essentially redefines the ampere using quantum phenomena.

Strategic international partnerships [419, 420, 421, 422, 423, 424]

France is a key participant in EU-wide quantum initiatives (including the European Quantum Flagship and EuroQCI) and has multilaterals agreements with countries like the United States, Germany, and the Netherlands, which have awarded over €30M in joint funding for quantum R&D projects; these quantum R&D projects address key priorities including scalable architectures for fault-tolerant quantum computing, photonic and superconducting systems integration, and hybrid platforms supporting quantum networking.

Multi-sector industry adoption and commercialization of quantum technologies [425, 426]

France's national strategy emphasizes rapid technology transfer and industrial adoption; their programs are designed to move quantum innovations from lab to market. Quantonation, Europe's first quantum-focused venture fund, plays a key role in scaling startups and attracting global investment. France is seeking to build a commercially viable quantum economy by integrating quantum technologies into sectors like finance, defense, and telecom. [427]

GERMANY

Structured national strategy with significant public investment [428, 429, 430, 431]

Germany's national strategy is anchored by the Quantum Technology Action Plan which seeks to establish a national quantum ecosystem by 2026. The plan brings €3B to support R&D projects and start-ups through 2026 to make Germany a world leader in quantum technologies. This investment supports the development of a universal quantum computer with a target of 100 qubits by 2026 and aims to expand to 500 qubits in the future. This effort is part of a broader strategy to secure technological sovereignty, stimulate economic innovation, and address societal challenges through quantum applications.

- **Ecosystem development:** Germany's strategy aims to establish a high-performance quantum ecosystem by fostering collaboration across stakeholder groups. The Action Plan calls for tight integration of all actors along the value chain and provides funding to research institutions and start-ups.
- **Public-private partnerships:** Germany's Technology Action Plan emphasizes the importance of early involvement of end users and industry partnership in shaping applications and standards. Initiatives like the Quantum Technology & Application Consortium (QUTAC) complement this goal through advocacy for strategic coordination and long-term public investments.

  QUTAC is a coalition of 14 leading German and EU-based companies (including, Bosch, Siemens, Deutsche Telekom, and BMW) that formed to accelerate the industrial application of quantum technologies. QUTAC conducts application-oriented research, is privately funded, and plays a key role in shaping Germany's digital sovereignty and competitiveness in quantum technologies.

- **EU Chips Act alignment:** [432] The EU Chips Act calls out the need to build up capacity for quantum chips and related semiconductor technologies. Germany's national quantum strategy aligns with this effort as they already working with EU partners on standards and infrastructure.
- **Quantum hardware development:** Germany supports multiple hardware approaches (e.g., superconducting, photonic, ion-trap) and aims to develop application-oriented quantum computing systems. In addition to the aforementioned universal quantum computer goal, the Action Plan also focuses on developing specialized hardware for targeted use cases.
- **Scalable quantum communication infrastructure:** The Action Plan prioritizes quantum communication and post-quantum cryptography, including the development of market-ready QKD components and migration to quantum-safe encryption for critical infrastructure. It also supports building a well-networked quantum communication industry in Germany.

International quantum diplomacy and bilateral agreements [433, 434, 435]

Germany is recognized as a top-tier quantum partner globally and is frequently cited in other countries' national strategies. Germany signed formal agreements with the United States and participates in the Quantum Development Group—a high-level multilateral forum of government representatives from allied nations, including the United States and Japan, which was created to coordinate national quantum policies, strengthen supply chains, and foster a global quantum ecosystem.

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Application-oriented research [436]
Germany emphasizes early involvement of end users and industry in shaping quantum applications. This ensures their quantum research is aligned with real-world needs and accelerated the development of market-ready solutions in sectors like automotive, telecommunications, and manufacturing.

Emphasis on workforce development and talent pipeline [437, 438]
Germany is investing in quantum education and talent development through initiatives like the Quantum Future Academy and targeted support for young researchers. They are working to address talent shortages in quantum software and commercialization by engaging students from physics, computer science, and engineering early in their careers. The Federal Ministry of Education and Research (BMB) supports several different programs ranging from school outreach to competitive awards (e.g., the Quantum Future Award) to help build a sustainable talent pipeline and foster long-term innovation capacity.

Standards development and global influence [439, 440, 441, 442, 443]
Germany plays a leading role in shaping international quantum standards, particularly in post-quantum cryptography. Its Federal Office for Information Security (BSI) contributes to EU-wide efforts to coordinate the transition to PQC, including the development of implementation roadmaps and technical guidelines. BSI's TR-02102-1 recommends hybrid cryptographic schemes as a secure migration strategy, reflecting Germany's technical leadership in PQC standards development. Germany's public sector has begun deploying quantum-safe encryption across critical infrastructure which aligns with their commitment to technological sovereignty. [444]

JAPAN

National strategy and quantum investments
Japan's national quantum strategy integrates large-scale public investment, long-term technical roadmaps, and cross-sector innovation hubs to accelerate quantum computing, communications, and industrial deployment.

- **Public investments; largest annual quantum investment:** [445] In 2025 (~30 June 2025), Japan committed ¥1.05 trillion (~$7.4 billion USD) to quantum R&D, marking the largest single-year quantum investment globally—accounting for "75% of all new public quantum funding worldwide." [446]
- **Quantum computing roadmap:** [447] Japan's Quantum Technology and Innovation Strategy Roadmap (2022) emphasizes ecosystem building and capability scaling through partnerships, research, and application development. Topical focus areas cover scalable architectures, cryogenic systems, superconducting qubits, fault-tolerant quantum computers, integration with HPC, quantum networks, etc. and goals include achieving large-scale quantum computing capabilities by 2040; 2040 technical targets include 1,000 physical qubits and 50 logical qubits
- **Quantum future industry development roadmap:** [448] Japan's Strategy of

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Quantum Future Industry Development (2023) builds on their quantum computing roadmap with its focus cross-sector applications and innovation hubs (i.e., Quantum Technology Innovation Hubs) that convene all stakeholder types (i.e., industry, academic, government). The future industry development strategy views quantum computing as a priority alongside AI and biotechnology; emphasis is placed on topics like modular quantum computing platforms and open-source software including Japan's OQTOPUS (Open Quantum Toolchain for Operators and Users), the framework used for their first domestically produced superconducting quantum computer.

Integrated approach to quantum systems development: The strategy explicitly calls for the integration of gate-based and annealing-based quantum systems—significant because it leverages the complementary strengths of both architectures to accelerate practical applications and broaden use-case coverage. [449] Japan is taking this approach for LASOLV, its proprietary annealing-based quantum hardware. LASOLV is currently one of the most advanced annealing systems globally and a cornerstone of Japan's push toward industrial-scale quantum optimization. [450]

- **National testbed and deployment infrastructure:** Japan's government established G-QuAT (Global Research and Development Center for Business by Quantum-AI Technology) as a national quantum testbed and innovation hub to accelerate industrialization and real-world deployment of quantum technologies. G-QuaT comprises three integrated platforms—ABCI-Q, Qubed, and Qufab—which exist to validate quantum components, simulate real-word use cases, and support commercialization through shared infrastructure and business incubation. [451, 452, 453]

  Japan's quantum infrastructure is being leveraged in international benchmarking and collaborative standards-aligned R&D through projects like Q-NEKO under the EU-Japan Digital Partnership. [454]

- **Quantum policy coordination:** Japan's Cabinet Office Council for Science, Technology and Innovation (CSTI) oversees quantum policy coordination and ensures alignment across ministries, industry, and academia. Japan participates in international quantum diplomacy and standards forums, including the Quantum Technology Innovation Council, which advises on ecosystem development and strategic implementation priorities. [455, 456]

Global partnerships and multi-stakeholder coordination:

- **Japan's Q-STAR is an industry-driven, non-profit, multistakeholder alliance:** [457] Japan's Q-STAR consortium (Quantum Strategic Industry Alliance for Revolution) plays a central role in coordinating industry use cases, developing middleware specifications, and promoting quantum adoption across sectors like logistics, finance, and medicine. Q-STAR has been accredited as Japan's "national mirror committee for ISO/IEC JTC 3," enabling Japan to shape international quantum standards directly. [458]

- **Japan's quantum strategy mandates participation in international standards bodies:** [459] The Future Industry Development strategy also highlights the need for international collaboration and standardization, explicitly mandating participation in international standards bodies. Japan currently participates in international committees including ISO/IEC JTC 1 (specifically its Working Group 3 on Quantum Computing), ISO/IEC JTC 3 on Quantum Technologies, and ITU-T Study Groups 13 and 17, which focus on quantum-safe networking and quantum key distribution. [460, 461] These international engagements ensure Japan aligns its domestic innovations with global standards so it can influence the development of foundational protocols, terminology, and interoperability frameworks for quantum systems.
- **Bilateral quantum cooperation agreements:** [462, 463, 464, 465, 466] Japan has signed bilateral quantum cooperation agreements with the United States, the European Union, and the United Kingdom to advance joint research, infrastructure development, and standards alignment. It also engages with Denmark and other countries through multilateral forums such as the G7 Quantum Working Group and the International Council of Quantum Industry Associations (ICQIA), which promote global coordination on quantum policy and interoperability.
- **Commercial leadership in quantum:** Japan's quantum ecosystem includes major industry players in quantum including NTT, Fujitsu, and Hitachi; these organizations contribute to hardware development, software platforms, and hybrid quantum-classical systems.

  Fujitsu co-developed Japan's first superconducting quantum computer and recently launched a 256-qubit superconducting system with RIKEN, aimed at scaling hybrid quantum computing capabilities globally. [467]

  NTT is advancing LASOLV, Japan's proprietary quantum annealing system, which . is designed for industrial-scale combinatorial optimization; it integrates quantum-inspired algorithms and is part of Japan's broader strategy to combine gate-based and annealing-based systems for practical applications. [468]

  Hitachi is pioneering silicon-based quantum computing through its "shuttling qubit" control method, which supports scalable architectures and error correction for large-scale quantum systems. [469]

Workforce development and education:

- **Japan's quantum strategy prioritizes workforce development:** [470] Japan's Quantum Technology Innovation Council has proposed a national quantum ecosystem strategy that prioritizes workforce development to maintain global competitiveness. These recommendations are being incorporated into the

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Integrated Innovation Strategy 2025, which guides Japan's science and technology budget and policy priorities.

- **Q-STAR's 2030 workforce goal:** [471, 472] The Q-STAR consortium promotes quantum workforce development by recruiting and training talent across startups, SMEs, large corporations, and academia. Their goal is to ensure quantum technologies are adopted and understood by 10 million users in Japan by 2030, part of a broader strategy to democratize quantum access.
- **G-QuAT's industry-academic collaboration:** [473] Japan's G-QuAT center (Global Research and Development Center for Business by Quantum-AI Technology) supports workforce development, joint R&D, personnel exchange, and infrastructure sharing with industry leaders like Fujitsu. This collaboration aims to strengthen Japan's global competitiveness in quantum by integrating academic research with industrial applications. A recent Fujitsu press release confirms its role in G-QuAT and highlights its contribution to developing Japan's first domestically produced superconducting quantum computer. [474]

NETHERLANDS

National strategy and public investments [475, 476, 477]

The Netherlands launched the Quantum Delta NL initiative in 2020–2021 through a €615 million grant obtained from the National Growth Fund to position the country as a leading international hub for quantum technology. The Quantum Delta NL initiative emphasizes public-private partnerships and supports coordinated research across five regional hubs and seeks to generate in the range of €5-7 billion in GDP impact and 30,000 high quality jobs over the long-term.

World-class research infrastructure investments

Quantum Delta NL is prioritizing investments in shared cleanroom facilities and infrastructure—such as NanolabNL and regional quantum hubs—to support collaboration among research institutions and to accelerate commercialization. [478, 479] Their strategy explicitly emphasizes the demonstration of modular, open-architecture systems (e.g., Tuna-5) as well as ecosystem-level co-development across startups, academia, and government to advance interoperability and strength domestic supply chain capabilities. [480, 481, 482]

- **Superconducting quantum processor Tuna-5:** [483, 484, 485] The Netherlands' superconducting quantum processor, Tuna-5, is available via public cloud. It was developed through the HectoQubit/2 project by QuTech, TNO, and four Dutch startups using an open-architecture model, which integrates modular hardware and software components. Tuna-5 serves as a system-readiness benchmark (rather than a production-scale machine) and is aligned with both national and EU quantum strategies as well as with OpenSuperQPlus—an EU Quantum Flagship project targeting a 100-qubit demonstrator by late 2026.

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Quantum standards leadership and pre-standardization efforts [486, 487]
Dutch organizations are actively engaged in quantum pre-standardization through contributions to ISO/IEC JTC 3, (i.e., the international committee focused on quantum standards) and their participation in EuroQCI and other EU-level initiatives. These initiatives aim to harmonize quantum communication protocols.

- **Purple NECtar Quantum Challenges:** [488, 489, 490] The Dutch Ministry of Defence (specifically its Materiel and IT Command, COMMIT) launched the Quantum Challenges, with the results to be showcased at the "Purple NECtar/Innovation in Defence" event in November 2025. The challenges specifically fund exploratory work in areas including quantum emulation (Fermioniq), photonic quantum computing (QuiX Quantum), quantum cryptography (Q*Bird), quantum timing/sensing (Qubitrium and Xairos), and quantum mapping (QuantaMap).

International partnerships and export controls in quantum [491]
The Netherlands plays a leading role in EuroQCI and SEEWQCI (South-East Europe to Western Europe Quantum Communication Infrastructure) which enables building cross-border quantum-secure networks with Greece, Bulgaria, and Cyprus via satellite and fiber links. [492, 493]

The country formed trilateral quantum R&D partnerships with France and Germany to award over €30 million in funding for joint projects focused on scalable computing, secure networks, and advanced sensing.

The NL continues to expand its international quantum partnerships, with formal agreements in place with France, Germany, the United States, the United Kingdom, and Japan, and active participation in multilateral dialogues involving 13 leading quantum nations.[494]

- **Export control-as-a-service platform:** In 2024, The Netherlands strategically implemented an export control-as-a-service platform through Quantum Delta NL in partnership with Export Control Group International; the partnership aims to help quantum start-ups and scale-ups navigate dual-use regulations and reduce compliance risks.[495] The initiative reflects the country's growing national concern over the potential misuse of quantum technologies, particularly in military and surveillance contexts. The platform serves as a compliance framework and intends to reduce costs, save time, and boost investor confidence through adherence with lawful and ethical operations. [496]

Quantum startup ecosystem and commercialization
In 2023, there were reportedly 23 quantum startups supported under Quantum Delta NL. [497, 498, 499] One source claims that more than 50 quantum startups are now supported in the Netherlands since the previously reported 2023 figure. [500] The ecosystem is distinguished by its open-architecture approach, which promotes modular integration across hardware and software platforms.

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- **Leading Dutch quantum companies:** QuiX Quantum, Qblox, Fermioniq, QuantWare, and QphoX are among the leading companies supported by Quantum Delta NL. QuiX Quantum is a European leader in photonic quantum computing hardware; Qblox provides scalable and modular control electronics; Fermioniq specializes in quantum-inspired software and emulation; QuantWare develops superconducting quantum processors for scalable computing; and QphoX is pioneering quantum transduction hardware to enable optical interconnects between quantum systems. [501, 502, 503]
- **Modular, open-architecture ecosystem:** The Dutch quantum ecosystem has an open-architecture approach which focuses on the integration of modular hardware and software components from multiple quantum vendors. The Tuna-5 quantum computer demonstrates this strategy through its combining of interoperable technologies into a publicly accessible system. The hybrid quantum-classical data center being built by QuiX Quantum and QMware reflects this approach of open quantum platform architecture. [504, 505, 506]

SWITZERLAND

Coordinated national strategy with expert governance [507, 508]

Switzerland has a federally mandated quantum strategy through its Swiss Quantum Initiative (SQI). SQI is coordinated and led by the Swiss Quantum Commission (SQC)—a group of leading experts in the field—and hosted by Swiss Academy of Sciences (SCNAT) to strengthen Switzerland's position in the field of quantum research, technology, and application. The initiative's goals are achieved through target research funding, education and workforce development, knowledge and technology transfer, and international cooperation.

The SQC pursues five areas of action:

1. **Targeted R&D Funding:** Defines frameworks for competitive research calls through the Swiss National Science Foundation (SNSF)
2. **Innovation Acceleration:** Guides innovation through a framework for managing innovation funding through competitive calls
3. **Infrastructure & Knowledge Transfer:** Coordinates national platforms for technology sharing and collaboration
4. **Workforce Development:** Designs curricula and evaluates strategies to meet high demand for quantum specialists
5. **Global Connectivity:** Strengthens international partnerships to align Swiss efforts with global quantum ecosystems

- **SQI is a mandated national strategy:** SQI was launched as a mandated national initiative to support quantum science and technologies; goals are achieved through target research funding, education and workforce development, knowledge and technology transfer, and international cooperation
- **Governance structure comprises quantum experts:** [509] SQC members are the top active and retired Swiss scientists; members are elected and work voluntarily

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- **Infrastructure and workforce and nationally coordinated:** SQI supports infrastructure development, knowledge transfer platforms, and curriculum design to meet growing demand for quantum specialists
- **Switzerland's strategy spans the full quantum value chain:** SQC makes recommendations for the full spectrum of commercial maturity—from basic research to industrial and societal applications

Dual-track sustained federal investment model fuel competitive research and innovation [510]

Switzerland committed over CHF 100M (~$125M USD) through 2028 to support both basic research (through the Switzerland National Science Foundation) and applied innovation (through Innosuisse, the Swiss Innovation Agency).

- **Supplemental private sector investments:** [511] Public investment in quantum technologies is increasingly complemented by private sector engagement; companies including IBM, ID Quantique, and Zurich Instruments play key roles in advancing research, infrastructure, and commercialization.

Global engagement and technical diplomacy

Switzerland leverages its international organizations to foster global cooperation and responsible development of quantum technologies.

- **Networking and public engagement events:** [512, 513] Switzerland organizes events including Quantum Industry Day and Swiss Quantum Week to help connect the Swiss quantum ecosystems with its international counterparts.
- **Swissnex Quantum Summit and GESDA Summit:** The Swissnex Quantum Summit connects international quantum experts from government, academia, and industry to promote cooperation and advance the quantum sector. [514] Separately, the annual GESDA Summit gathers scientists, diplomats, and innovators to anticipate how new scientific discoveries, including quantum, can help solve critical global issues. [515]
- **The Open Quantum Institute (OQI) at CERN:** OQI serves as a neutral, multilateral science diplomacy platform that promotes global access to quantum computing for societal benefit. [516]

UNITED KINGDOM

Strategic national investment for quantum technologies [517, 518, 519]

The UK's Quantum National Strategy aims to position to lead global quantum standards by 2033 and commits £2.5 billion over 10 years to achieve this goal. The UK National Quantum Strategy also commits to position the UK as a quantum-enabled economy by 2033. Their strategy outlines four goals:

1. world-leading research
2. business support
3. technology adoption
4. regulatory leadership

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Additional investments include £670M for quantum computing and £160M for commercial deployment and workforce development. [520]

Infrastructure and innovation ecosystem [521, 522]
The National Quantum Technologies Programme (NQTP) provided initial funding to four Quantum Technology Hubs focused on computing (Oxford), sensing (Birmingham), imaging (Glasgow), and communications (York). The NQTP received a 10-year funding guarantee to support long-term planning and sovereign capability development. Through NQTP, the UK hosts more than 180 quantum organizations—including startups, SMEs, and international companies—who are connected to 140 Hub industry partners. [523]

Global standards participation
The British Standards Institution (BSI) is the UK's national standards body and is a central actor in global quantum standardization through its role leading the ISO/IEC Joint Technical Committee on Quantum Technologies. [524, 525]

- **Key international standards coordination:** The UK's National Physical Laboratory (NPL) coordinates UK involvement in various international standards bodies, including ETSI, ISO, IEC, and ITU. The UK contributes to standards development across multiple quantum applications, including QKD, quantum random number generation, and quantum sensing and computing architectures.
- **Standards Network Pilot:** In November 2023, the UK's NPL and partners, including the BSI and the Department for Science, Innovation and Technology (DSIT), launched the Quantum Standards Network Pilot—a £14 million program that seeks to evolve into a national center for quantum standards to ensure UK influence in international forums. [526, 527]

Sovereign quantum capabilities [528, 529]
The UK's National Quantum Strategy has a stated goal of developing "sovereign quantum capabilities" amidst "concerns over foreign acquisition of UK-based quantum firms" (such as Oxford Ionics and the quantum unit of Oxford Instruments by U.S. entities) and to avoid dependence on foreign infrastructure. The CEO of Universal Quantum (Sebastian Weidt) recently told Parliament's Science, Innovation and Technology Committee that "the UK risks losing its global lead in quantum computing without faster government investment, procurement, and manufacturing support." [530]

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COMPARISON OF QUANTUM INVESTMENTS ACROSS COUNTRY

Country	Investment Amount	Notes
Canada	$1B+ (cumulative)	$360M from National Quantum Strategy + $384M NSERC + $74M in 2025 grants
China	$15.3B (cumulative)	Largest global public investment; focused on quantum communications and cryptography
France	€1.8B (~$1.9B)	National Strategy launched in 2021; includes MetriQs-France and BACQ benchmarking
Germany	€3B (~$3.2B)	Quantum Technology Action Plan through 2025; supports research, startups, and infrastructure
Japan	¥1.05 trillion (~$7.4B)	Largest single-year quantum investment globally; includes R&D acceleration and infrastructure expansion.
Netherlands	€615M (~$660M)	Quantum Delta NL initiative; €273M awarded in 2024, €342M earlier
Switzerland	CHF 100M+ (~$125M)	Includes CHF 20M (2023–24) and CHF 80M (2025–28) via Swiss Quantum Initiative
United Kingdom	£2.5B (~$3.1B)	10-year National Quantum Strategy; includes £670M for computing and £160M for deployment
United States	$3.2B+ (cumulative)	Includes $1.8B from NQI Act, $1.2B+ from DOE (NQISRCs), $700M from Illinois, and additional state-level investments

INDUSTRY CONSORTIA OR PUBLIC-PRIVATE PARTNERSHIPS

DARPA Quantum Benchmarking Initiative (QBI) [531]

The Quantum Benchmarking Initiative (QBI), launched by DARPA, is designed to determine whether utility-scale quantum computers can be built significantly faster than conventional predictions (i.e., such that their computational value exceeds their costs) by 2033. QBI provides unbiased third-party verification of quantum computing pathways to utility-scale operation and communicates the results of these efforts to U.S. government stakeholders. QBI engages industry leaders such as Microsoft and PsiQuantum in a staged validation process: concept development (Stage A), risk mitigation planning (Stage B), and prototype verification (Stage C). Nearly 20 companies have entered Stage A, including Microsoft and PsiQuantum. [532]

DOE National Quantum Information Science Research Centers (NQISRCs)

DOE funds five major NQISRCs—Q-NEXT, C2QA, SQMS, QSA, and QSC—that integrate national labs, academia, and industry to advance quantum computing, sensing, networking, and materials science. [533, 534] The NQISRCs contribute to pre-standardization research by developing prototype quantum platforms, benchmarking quantum system performance, and identifying interoperability requirements for future quantum infrastructure. These centers involve over 1,500 researchers across 115 institutions and represent the largest single federal investment in quantum technologies, with DOE committing $575M over five years and an additional $625 million announced in 2025 to expand the program. [535, 536]

European Quantum Industry Consortium (QuIC) [537]
The European Quantum Industry Consortium (QuIC) was founded in 2021 as a pan-European not-for-profit association that seeks to accelerate the growth and competitiveness of Europe's quantum technology sector. QuIC comprises nearly 200 member organizations that work together to shape strategic roadmaps, inform policy, and support commercialization across quantum computing, communications, sensing, and simulation. The consortium engages in pre-standardization activities, develops intellectual property strategies, and coordinates with European institutions and global partners to position Europe as a leader in quantum innovation. Their working groups also contribute to activities that focus on standards, education, and industrial use cases, and they expect to launch a European Quantum Standards Roadmap in 2026 to incentivize participation in European and international standards development. [538]

Global Quantum Leap (GQL) [539, 540]
GQL received grant funding from NSF through its AccelNet program. They seek to accelerate the development of next-generation quantum computing and communications systems by "linking nanofabrication infrastructure with quantum information sciences." Proclaimed to be the international "network of networks," GQL convenes the nodes of the NSF-funded National Nanotechnology Coordinated Infrastructure (NNCI) and complementary networks in the United States to foster collaboration, workforce development, and technology roadmapping. GQL's activities support international research exchanges, workshops, and educational boot camps with institutions such as NIMS in Japan and RWTH Aachen in Germany. Their contributions to quantum standards development focus on pre-standardization activities including identification of tools and process needs for quantum devices, roadmap development, and alignment of nanofabrication capabilities with quantum system requirements.

International Council of Quantum Industry Associations (ICQIA) [541, 542, 543, 544]
The ICQIA was formally established in 2023 through a memorandum of understanding signed by the world's four leading national and regional quantum consortia: Quantum Industry Canada (QIC), the Quantum Economic Development Consortium (QED-C), the Quantum Strategic Industry Alliance for Revolution (Q-STAR), and the European Quantum Industry Consortium (QuIC). ICQIA aims to strengthen global coordination across the quantum ecosystem by facilitating communication, aligning policy approaches, and supporting the development of supply chains, talent exchange, and open markets. ICQIA offers a platform for discussing common priorities like international standards, intellectual property

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frameworks, and equitable access to funding. It has also taken on a more strategic role in standards development by advocating for quantum's inclusion in the G7 agenda, convening panels to advance interoperability across borders, and framing standards as essential infrastructure for a globally connected quantum economy.

NSF Quantum Leap Institutes [545, 546]

The NSF funds Quantum Leap Challenge Institutes (QLCI) as large-scale, interdisciplinary research centers focused on advancing quantum computing, sensing, simulation, and hybrid architectures. The institutes support foundational research and foster collaboration across stakeholder types to accelerate quantum innovation and infrastructure development. While not explicitly charged with addressing standards development, their research outputs and partnerships may inform future standardization efforts through prototype systems, performance validation, and cross-sector engagement. As of 2025, NSF has funded 5 QLCI institutes, each receiving $2-7.5M over six years: [547, 548]

1. CIQC: Challenge Institute for Quantum Computation
2. Q-SEnSE : Quantum Systems through Entangled Science and Engineering
3. HQAN: Hybrid Quantum Architectures and Networks
4. QuBBE: Quantum Sensing for Biophysics and Bioengineering
5. RQS: Institute for Robust Quantum Simulation CIQU

Q-STAR (Quantum STrategic industry Alliance for Revolution) [549]

Q-STAR is a Japan-based consortium founded in 2021 to promote the industrialization of quantum technologies through cross-sector collaboration among startups, SMEs, large corporations, and academic institutions. Q-STAR supports business development, workforce training, and international partnerships, and serves as Japan's "national mirror committee" to IEC/ISO JTC 3 on quantum technologies. They also aim to enable widespread quantum adoption by 2030 with a goal of reaching 10 million users in Japan.

Quantum in Space Collaboration (QSC) [550, 551, 552]

The Quantum in Space Collaboration is a public-private partnership led by DOE) through its Office of Technology Transitions. QSC focuses on revolutionizing space innovations by advancing quantum technologies. Its industry partners include Boeing, Axiom Space, Universities Space Research Association (USRA), Vescent, Qrypt, Infleqtion, Accenture, and Nebula. QSC provides feasibility assessments and demonstrations of quantum sensing, communications, and hybrid quantum computing in orbital environments. QSC is envisioned as a platform for deploying secure quantum networks, space-based datacenters, and quantum-enabled resource exploration and manufacturing.

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Quantum Industry Canada (QIC) [553]
QIC is a national, business-led consortium uniting over 65 Canadian quantum companies and allied organizations to accelerate the commercialization of quantum technologies. QIC received $1.4M in federal funding in 2023 under Canada's National Quantum Strategy to support international collaboration and help position Canadian firms for global leadership. QIC does not directly develop technical standards for quantum technologies but does contribute to international coordination efforts through its founding role with ICQIA, which promotes shared priorities such as supply chain development, talent exchange, and policy alignment.

U.S. Quantum Economic Development Consortium (QED-C)
The QED-C)was established in 2018 by NIST under the National Quantum Initiative Act (NQI) and is managed by SRI as a public-private partnership comprising more than 180 member organizations. [554, 555] QED-C operates technical advisory committees on quantum computing, networking, sensing, and standards, and has contributed to interoperability guidelines, benchmarking frameworks, and terminology references including the NIST Single Photo Sources and Detectors Dictionary (NIST IR 8486). [556] The consortium plays a key role in identify pre-standardization needs and aligning industry priorities with federal quantum initiatives.

U.S. FEDERAL AGENCY ROLES

Federal agencies play distinct and complementary roles in shaping the quantum standards landscape. Their contributions span technical leadership, strategic coordination, and targeted investments that support the development, validation, and adoption of quantum technologies. Agencies such as NIST, NSF, DOE, DoD, NASA, and OSTP are advancing efforts in areas like benchmarking quantum systems, funding standards-related research, convening stakeholders, and aligning quantum innovation with national priorities.

The tables that follow summarize each agency's involvement, highlighting how their initiatives collectively support a robust and interoperable quantum ecosystem.

National Aeronautics and Space Administration (NASA)

Key Role
Develops and tests quantum technologies for space-based communications, sensing, and navigation; supports quantum metrology and contributes to interagency standardization efforts through partnerships with NIST and OSTP [557, 558]

Contributions
- **Aligns quantum research with the National Quantum Initiative (NQI) and OSTP's strategic vision** including development of a space-based quantum communications testbed and coordination with interagency quantum networks research [559] **Collaborates with NIST on quantum metrology standardization**

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through formal interagency agreement to co-develop quantum measurement capabilities for terrestrial and flight-based quantum networks [560]

- **Convenes interagency and academic partnerships to advance quantum communications and sensing technologies;** engages in roadmap development and public-private collaboration to support scalable quantum infrastructure and standards [561]
- **Develops quantum communications and networking testbeds through NASA's SCaN program** including space-based entanglement sources, ground station upgrades, and system architecture studies; supports future standards for free-space quantum networking and synchronization [562]
- **Establishes quantum metrology capabilities at NASA Glenn Research Center** to support precision measurements, device validation, and modeling for quantum systems; contributes to standardization of quantum sensors and timing systems for aerospace environments [563]
- **Leads quantum sensing R&D for space missions,** including atomic clocks, magnetometers, interferometers, and photon detectors; contributes to standardization of quantum sensors for aerospace environments through technical assessments and prototype deployments [564]

National Institute of Standards and Technology (NIST)

Key Role

Lead technical agency for quantum standards development and fundamental research

Contributions

- **Administers the U.S. Technical Advisory Group to ISO/IEC JTC 3** for coordinating U.S. engagement in international quantum standardization efforts [565]
- **Advances deployable quantum measurement technologies through the NIST on a Chip (NOAC) program** and translates laboratory-scale quantum measurement science into miniaturized, industry-relevant sensors and timekeeping technologies [566, 567]
- **Awarded Nobel Prize in Physics for pioneering experimental quantum metrology techniques** that "enable the measurement and manipulation of individual quantum systems;" contributions laid foundational groundwork for quantum computing, precision timekeeping, and quantum metrology [568]
- **Contributes to quantum materials and fabrication pre-standardization through collaboration with national laboratories** and works with Fermilab's Superconducting Quantum Materials and Systems (SQMS) Center to improve qubit fabrication processes and reduce material-induced losses [569]
- **Designs and evaluates quantum networking references architectures—** including entanglement distributions, routing, and hybrid classical-quantum integration—through lab programs and multi-node testbeds

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- **Develops cryogenic superconducting control electronics for scalable quantum systems;** supports next-generation quantum computing systems by advancing Single Flux Quantum (SFQ)-based superconducting electronics; enables ultra-fast digital logic and scalable quantum control architectures
- **Develops quantum measurement tools and foundational metrology for quantum systems** and conducts research across quantum computing, sensing, and networking to establish reproducible calibration methods and performance evaluation frameworks that underpin future quantum standards into future quantum measurement capabilities [570]

  Developed the BenchQC toolkit for quantum algorithm benchmarking to evaluate the performance of algorithms such as the Variational Quantum Eigensolver (VQE) quantum algorithms under realistic noise conditions [571]

  Leads development of quantum network metrology and references architectures across NIST laboratories including the Information Technology Laboratory (ITL), Communications Technology Laboratory (CTL), Material Measurement Laboratory (MML), and Physical Measurement Laboratory (PML); [572, 573] supports interoperable and measurable quantum networking systems

- **Develops quantum repeaters, atomic clocks, single-photon sources, and detectors** that enable long-distance quantum communication; led improvements in quantum sensing in radio signals, defective transistors, and acoustic vibrations [574, 575]
- **Develops strategic quantum technology roadmaps and measurement roadmaps** through multiple NIST laboratories to guide multi-year research priorities in which guide 5–7-year research priorities across quantum communications, metrology, calibration services, and quantum networking; roadmaps guide foundational standards development and future infrastructure investments for scalable quantum systems and secure quantum networks [576]
- **Guides the development and validation of encryption cryptographic algorithms resilient to quantum threats** through national cryptographic competitions and validation programs that support secure migration to post-quantum cryptography across federal systems and critical infrastructure designed to withstand the assault of quantum computers through competition; included encryption tools in NIST's post-quantum cryptographic standard [577]
- **Leads Mega-Qubit Innovations in Measurement Science Program** to develop ultrasensitive cryogenic microwave measurement tools and enable scalable quantum computing architecture with millions of qubits [578]
- **Established the Quantum Economic Development Consortium** in partnership with SRI International to convene industry, academia, and government stakeholders, identify pre-standardization needs, and align research and

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development priorities in quantum computing, sensing, and networking and boost U.S. leadership in quantum technologies; convenes stakeholders to identify standards needs and support pre-standardization efforts in quantum computing, sensing, and networking [579]
- **Founded DC-QNet multi-node quantum testbed** (in partnership with NASA, NSA, USNO, DEVCOME ARL, and NSA/CSS-RES) to evaluate quantum networking technologies and support secure quantum communications and ultra-precise time synchronization [580, 581, 582]
- **Leads the Quantum Voltage Project and foundational quantum metrology efforts** and applies quantum phenomena to redefine and disseminate SI electrical units, enabling ultra-precise, internationally traceable measurement standards [583]
- **Operates the Joint Quantum Institute (JQI)** in partnership with University of Maryland and the Laboratory for Physical Sciences; serves as world-class center for quantum research and education; JQI advances foundational quantum science and develops quantum-enabled technologies (e.g., chip-scale frequency combs, low-noise lasers, integration photonics for quantum metrology, atomic clocks, secure communications) [584, 585]

National Science Foundation (NSF)

Key Role
Funds academic research and workforce development in quantum technologies; provides sustained investments in research, infrastructure, and workforce development; supports pre-standardization activities and testbed development that lay groundwork for future quantum standards

Contributions
- **Enables “quantum foundries” infrastructure for rapid prototyping of quantum materials and devices** through the Q-AMASE-i program (Quantum Accelerated Discovery Foundries for Materials Science, Engineering, and Information); these foundries are designed to accelerate quantum materials design, synthesis, and characterization, as we as translate fundamental research into interoperable components for quantum systems and networks [586]
- **Launched the ExpandQISE Program to foster quantum R&D partnerships** between established and emerging institutions to broaden participation in quantum R&D and promote consistent practices across diverse research environments [587]
- **Launched the National Quantum Virtual Laboratory (NQVL) to lower the barriers to access in quantum information science** through offering a networked platform integrating hardware, software, testbeds, and training tools; [588] provides researchers with remote access to quantum testbeds, simulators, and digital twins

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- **Runs the Quantum Leap Challenge Institutes** which help accelerate breakthroughs in computing, networking, and sensing [589]
- **Supports university–industry partnerships for quantum innovation,** including a Regional Innovation Engines (NSF Engines) Development Award with Chicago Quantum Exchange [590]

National Security Agency (NSA)

Key Role
Leads U.S. government transition planning to post-quantum cryptography to protect national security systems [591]

Contributions

- Issued future quantum-resistant algorithm requirements for National Security Systems—the Commercial National Security Algorithm Suite 2.0 (CNSA 2.0)—which outlines future quantum-resistant algorithm requirements for National Security Systems; adoption will follow NIST's finalization and validation of PQC standards [592]
- Participates in interagency quantum networking initiatives including DC-QNet, a multi-node testbed for secure quantum communications, entanglement distribution, and time synchronization in the Washington, D.C. area [593]
- Released quantum-resistant algorithm requirements known as the Commercial National Security Algorithm Suite 2.0 (CNSA 2.0) requirements for National Security Systems (NSS); these requirements align with NIST's PQC standardization efforts [594, 595]

Co-authorized guidance document "Quantum-Readiness: Migration to Post-Quantum Cryptography" with NIST which complements NIST's PQC standardization process and extends the CNSA 2.0 effort by providing practical recommendations for migration and readiness; guidance document purpose is to help stakeholders prepare for adoption of standards being finalized for NIST [596]

Office of Science and Technology Policy (OSTP) & National Quantum Coordination Office (NQCO)

Key Role
Provides quantum leadership through policy and coordination under the National Quantum initiative Act

Contributions

- **Chairs interagency quantum subcommittees** under NSTC including the Subcommittee on Quantum Information Science (SCQIS) and the Subcommittee on Economic and Security Implications of Quantum Science (ESIX) which guide national quantum strategy, coordinate agency activities, and produce foundational policy documents [597]

CET: Quantum Technologies

- **Coordinates the National Quantum Initiative (NQI)** across NIST, NSF, DOE, DOD, NASA, and NSA; ensures strategic alignment of quantum R&D, workforce development, and infrastructure investments to maintain U.S. leadership in quantum technologies [598]
- **Facilitates international quantum cooperation** including bilateral agreements with six countries and a multilateral dialogue with 12 nations; launched the Entanglement Exchange as a deliverable to promote global collaboration in quantum networking and standards [599]
- **Launched the National Q-12 Education Partnership** in collaboration with NSF and industry leaders—including Boeing, AWS, Google, IBM, IEEE, Microsoft, and Rigetti—to integrate quantum concepts into K-12 education and expand early exposure to quantum science [600]
- **Managed development of multiple strategic quantum documents** including the *National Strategic Overview for Quantum Information Science* (2018)—the first government-wide plan for QIS—and the **National Strategic Plan for Quantum Information Science and Technology Workforce Development** (2024) which outlines actions to expand the quantum talent pipeline and strengthen U.S. competitiveness [601, 602]
- **Oversees the National Quantum Coordination Office (NQCO),** established by the National Quantum Initiative Act, housed within OSTP; coordinates federal quantum research, supports interagency collaboration, and promotes early access to quantum technologies across government, academia, and industry [603]
- **Supported demonstration of new protocol—Certified Quantum Randomness—**in collaboration with Argonne National Laboratory, Oak Ridge National Laboratory, JPMorganChase, Quantinuum, and the University of Texas at Austin; the protocol generates mathematically verifiable randomness using quantum entanglement, enabling secure applications in cryptography, privacy, and fairness [604]
- **Supports the National Quantum Initiative Advisory Committee (NQIAC),** which provides independent assessments and strategic recommendations to the President and Congress on quantum networking, workforce, and national competitiveness [605]

U.S. Department of Defense (DoD)

Key Role

Accelerates quantum technology adoption for national security applications including sensing, navigation, communications, and computing; supports the development, testing, and standardization of quantum technologies for defense missions through research laboratories, innovation units, and strategic partnerships; mandated by Congress to define long-term quantum challenges and update technical goals to ensure strategic alignment and measurable progress in quantum technology development [606, 607, 608]

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Contributions

Invested in building a quantum-capable workforce across seven defense laboratories including 255 staff working on quantum projects, 41 STEM education programs, and 400+ students [609]

- **Transition of Quantum Sensing (TQS) program:** [610] Part of the DoD's Defense Innovation Unit (DIU), the TQS program focuses on field-testing quantum sensors for military use across five critical areas – works to accelerate adoption of quantum technologies: inertial sensors, gravimeters, magnetic anomaly detection, magnetic navigation, and technology insertions and component development

  Partnered with the Air Force Rapid Capabilities Office (AFRCO) to demonstrate quantum inertial sensing in space; marked the first space-based demonstration of a quantum sensor [611]

  Partnered with Vector Atomic and Honeywell Aerospace to demonstrate first atomic gyroscope; demonstrated quantum inertial sensing capabilities to support GPS-independent navigation [612]

U.S. Department of Energy (DOE)

Key Role

Leads U.S. quantum innovation by funding and coordinating national labs to develop quantum computing, networking, sensing, and materials through large-scale research centers and testbeds

Contributions

- **ARPA-E Quantum Computing for Computational Chemistry (QC3) program:** [613] ARPA-E launched the QC3) program to apply quantum computing to urgent challenges in energy and materials science; QC3 supports the development of scalable quantum algorithms for computational chemistry; QC3 aims for a 100x performance improvement over classical methods in areas like industrial catalysts, superconductors, and battery chemistries
- **Invests millions in R&D** for quantum technologies, including $65 million in funding for 10 projects and 38 awardees, and $71 million for 25 projects in high-energy physics [614, 615]
- **Manages the National Quantum Information Science (QIS) Research Centers,** five centers performing research and developing technologies in quantum computing, communication, sensing, and materials; each center is a collective of labs, universities, and companies tackling problems in science, energy, security, communication, medicine, finance, and logistics [616]

Opportunities/ Recommendations

- **Supports quantum research through the national labs:**

  Created some of the world's largest quantum testbeds, including a 52-mile quantum loop between Argonne and Fermilab which will help explore quantum engineering systems and quantum entanglement [617]

  Exploring quantum materials through advanced x-ray techniques at Brookhaven National Lab [618]

  Realized Certified Quantum Randomness through Argonne and Oak Ridge National Labs, enabling practical potential real-world use cases [619]

Opportunities/ Recommendations

Drawing on the gaps and stakeholder priorities identified throughout this assessment, **the following recommendations aim to guide ASCET's strategic engagement in quantum standardization.** The recommendations are based on observed gaps, emerging needs, and stakeholder inputs gathered from government documents, industry roadmaps, strategic initiatives, and academic research. These opportunities are intended to support future planning, align with ASCET's engagement with stakeholder priorities, and reinforce its role in shaping responsible and effective standards for quantum technologies.

COORDINATE INTERNATIONAL EFFORTS TO REDUCE FRAGMENTATION IN QUANTUM STANDARDS [620, 621, 622, 623]

As quantum technologies advance globally, the lack of coordinated standards development across countries risks creating fragmented technical ecosystems and regulatory misalignment. Unified international approaches can streamline contributions, promote interoperability, and ensure coherence in the global market, helping to address emerging challenges in cross-border collaboration, trust, and scalability. Ongoing efforts by ISO, IEC, ANSI, and UNESCO are laying the groundwork for harmonized standards that support innovation while reducing duplication and inefficiencies.

ENABLE CROSS-PLATFORM COMPARISONS WITH MODULAR, APPLICATION-ORIENTED BENCHMARKING FRAMEWORKS [624, 625, 626, 627, 628, 629, 630]

As quantum computing platforms diversify, there is a growing need for benchmarking frameworks that allow consistent performance comparisons across different hardware and software environments. QED-C, TU Delft (Delft University of Technology), QPack, BACQ, and Sandia National Labs have all developed modular, application-oriented benchmarks that enable evaluation of quantum systems based on real-world tasks. These benchmarks also capture metrics like fidelity, execution time, and resource usage. This approach addresses current gaps in reproducibility and interoperability and helps researchers and developers assess trade-offs and optimize performance. Ongoing efforts by academic and industry stakeholders are expanding these frameworks to include hybrid quantum-classical systems and broader algorithm classes.

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ESTABLISH A QUANTUM TECHNOLOGY QUALITY MANAGEMENT SYSTEM (QT-QMS) [631, 632, 633]

A group of legal and policy experts have proposed the development of a QT-QMS to guide responsible innovation and streamline regulation in quantum technologies. This framework would incorporate legal, ethical, societal, and technical considerations while supporting testing, deployment, and risk management efforts. If developed in collaboration with SDOs such as ISO and IEC, the QT-QMS could serve as a global template for quantum governance. It could also integrate existing standards—such as ISO 27001 for information security, ISO 27005 for risk management, and ISO 42001 for AI governance—to ensure compatibility with current best practices. The proposed system is conceptually similar to ISO 13485 which governs quality management in the medical device industry. The recent launch of ISO/IEC JTC 3 further supports the feasibility of a coordinated, standards-based approach to quantum technology governance.

LAY GROUNDWORK FOR FOUNDATIONAL QUANTUM STANDARDS (DEFINITIONS, BENCHMARKS, METADATA, INTEROPERABILITY, CERTIFICATION FRAMEWORKS) [634, 635]

As quantum technologies continue to evolve, there is a critical need to establish foundational standards that define key concepts, performance benchmarks, metadata structures, and interoperability protocols. These standards will enable reproducibility, facilitate cross-platform comparisons, and support the development of certification frameworks that ensure trustworthiness and responsible deployment. Early standardization efforts can shape the trajectory of quantum innovation before regulatory mandates are introduced, helping to align technical progress with societal and ethical expectations.

STANDARDIZE QUANTUM SENSORS FOR MATERIALS CHARACTERIZATION

Current tools for characterizing materials defects are inefficient, according to a Google Quantum AI research study. [636] The study recommends development of tools that are faster and more specialized than qubits for use as sensors. These tools should be able to analyze qubit materials during manufacturing and link surfaces to performance issues. “Standardized sensors, like modified transmon qubits designed to measure environmental interference, could also help create a shared testing framework for the quantum industry. Initiatives like the Boulder Cryogenic Quantum Testbed aim to fill this gap by offering standardized measurement services to hardware developers.” [637] ASCET could collaborate with existing efforts or develop something independently.

STRENGTHEN WORKFORCE PIPELINES THROUGH INDUSTRY-ACADEMIC PARTNERSHIPS [638]

ASCET can help address persistent workforce gaps in quantum standardization by facilitating partnerships between academia and industry that offer hands-on experience through internships, testbed access, and collaborative R&D. The quantum workforce pipeline remains underdeveloped; there are limited structured pathways for students to gain interdisciplinary training across relevant fields including physics, computer science, and engineering. A recent analysis of course catalogs from 1,456 U.S. institutions found that only 61 offer dedicated quantum information science and engineering (QISE) degree programs; most of these are concentrated at Ph.D.-granting universities with limited undergraduate exposure

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across disciplines. [639] The U.S. National Science Foundation recently made a $39 million investment to establish partnerships between quantum programs and institutions seeking to build quantum research and training capacity. Research projects and internships must be agile and account for the pace by which quantum technologies evolve. [640]

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176 https://www.quantum.gov/wp-content/uploads/2024/12/DOE_QIS_Roadmap_Final.pdf

177 https://www.euroquic.org/strategic-industry-roadmap-2025/

178 “The development of QC solutions encompasses a wide range of technologies, from hardware systems to software tools… These QC landscape dimensions are represented by layers of abstraction like those used to describe traditional computing systems.” “In the remaining sections of this chapter, we provide details on the state of development of products and services and present the industry’s ambitions for each stack layer on the road to 2035.”

179 “Entities in the US and Asia currently dominate today’s supply chain… the growth of European suppliers is of prime importance.” “Europe faces challenges in securing supplies of critical raw materials… Addressing these gaps is crucial for Europe to avoid supply chain vulnerabilities.” “Insight into the current strengths and weaknesses of the European ecosystem from a supply chain perspective is essential for steering strategic investment decisions.”

180 “Standardisation is fundamental for the future of qubit control… an agreed framework… could lead to faster iterations of hardware designs.” “When defining benchmarks, there is a need to go beyond ‘quantum volume’… These benchmarks must also include energy consumption metrics.” “Europe is on track to begin the first QKD security certification within a few years… but must accelerate efforts.”

181 “The most powerful quantum computers in the world are not on European soil… enterprises need to send their data outside the EU.” “Improve availability of European quantum hardware in the cloud, operated by European cloud providers to ensure European autonomy.”

182 “The number of quantum experts in business is still very limited… software departments are counted for classical software projects.” “QURECA projects 600,000 new QT jobs by 2040… current skills gap necessitates upskilling and international talent recruitment.”

183 “EU startup valuations in 2022 were 30% of US equivalents; funding was half.” “The risk of an ‘extinction event’ for EU quantum scaleups is real.”

184 “Quantum computers can also be used as accelerators in combination with classical computers to run hybrid quantum/classical algorithms…” “Develop a suitable middleware for QC-HPC integration.”

185 “Almost all commonly used general-purpose quantum SDKs are developed by US companies… This has very profound implications for Europe.” “Supporting these companies… could offer a competitive advantage to European businesses.”

186 “Riverlane produced the world’s first decoder ASIC… enabling the simultaneous processing of error-prone data.” “Demonstrate real-time error correction cycles suppressing the logical error rate below the physical error rate for each of the main qubit technologies.”

187 “Multiverse Computing… makes use of quantum and quantum-inspired technologies in real applications for corporate customers.” “Support the development of algorithms for co-design QPUs which use resonators as computational elements.”

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188 “Quantum sensors are relevant to almost all areas of industry... some products intended for materials research have reached TRL 9 and are already available on the market.”

189 “Photonic QC... allows computing power to be scaled by connecting separate QPUs with no need for matter-to-photon qubit transduction.” “Deploy non-local error correction codes with a highly favourable logical-to-physical qubit ratio.”

190 “The EuroQCI will integrate QTs and quantum systems into terrestrial fibre-optic communications networks.” “Quantum keys and PQC will be adopted and/or integrated by apparatus operating at the various OSI layers.”

191 https://standards.ieee.org/industry-connections/activities/standardization-roadmap-on-quantum-applications/

192 https://www.sri.com/wp-content/uploads/2023/11/QTMR-Final-Report-of-Needs-Capabilities-and-Gaps-v5.pdf

193 “Depending on the application, materials are needed with specific optical, thermal, electrical, defect, and other properties.”

194 “There is not one universally used platform or approach, no standard configuration or set of components and materials.”

195 “Several participants highlighted supply chain needs, such as greater domestic supply of components and higher quality materials.”

196 “TWG [Technology Working Group] participants indicated they need more information on needs to address the ultra-high vacuum chamber/pump system needs...They do not see a movement towards standardization.” “TWG [Technology Working Group] participants are amenable to more sharing in principle, but any shared information must be clearly and narrowly defined.”

197 “TWG [Technology Working Group] participants indicated that the industry lacks sufficient quantum-knowledgeable hardware engineers.”

198 “Suppliers are reluctant to invest in new technology until their customers...are willing to commit to large sales volumes, but customers are reluctant to commit...until they see the technology they need.”

199 “Customized tools typically allow integrators more flexibility...but the low purchase volume leads to high prices.”

200 “Tool makers are unsure when or whether quantum demand will be sufficient to incentive development of dedicated quantum tools.” “Technology suppliers do not see commercial production growing and fear investing in new technology development, such as crystal growth technology, that gets superseded by new technology.” “Developing the new bandgap materials described in Figure 38 would require tens of millions of dollars...project participants don’t see much progress likely without government funding.”

201 “Participants pointed to the National Quantum Information Science Research Centers...as an example of white box centers...Acknowledging that testbed access is expensive, participants proposed facilitating broader access via government support.”

202 “Both PG and TWG participants discussed the prospects of using machine learning (ML) for a variety of materials research applications.”

203 “We recommend each quantum application (i.e., communications and networking, computing, sensing) develops its own roadmap. The specific metrics and needs vary drastically by application.”

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204 "They suggest reskilling existing CMOS test engineers and providing them with technology that has been designed with features to facilitate testing and quality control." "TWG participants agreed that technician usable systems compose an important goal."

205 Different quantum systems require precise wavelengths for tasks like qubit control, photon generation, and quantum communication.

206 "TWG [Technology Working Group] participants indicated it would be helpful for developers and integrators to consolidate their needs around a specific set of wavelengths to help generate critical mass in demand."

207 "A next iteration should seek more international involvement. Many countries have unique specializations."

208 "We found the opportunity for direct dialogue to be highly valuable...manufacturers can better align with industry."

209 "They suggested existing semiconductor design tools...could be modified for use with qubits."

210 White-box testbeds refer to experimental platforms that provide users with full transparency, control, and configurability of system components; this enables detailed observation, customization, and debugging of quantum technologies.

211 "They suggested a government-sponsored grand challenge could help accelerate this process." "Project participants don't see much progress likely without government funding."

212 https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q04_standardizationroadmapquantumtechnologies_release1.pdf

213 https://www.weforum.org/publications/state-of-quantum-computing-building-a-quantum-economy/

214 "No hardware platform has reached [level 4] yet, as it would signify demonstrating a quantum advantage on a real-world application." "Most quantum applications with provable advantage over classical methods (including breaking encryption) will require a large-scale quantum computer to realize."

215 "There are currently no policies regarding quantum computing and its energy usage. Introducing such policies should be considered to ensure future scalable technology that isn't at the expense of enormous energy costs."

216 "Asia, North America, Europe and Australia have very different innovation ecosystems. Consequently, national governments follow different pathways in the quantum computing journey."

217 "Standards on interoperability and performance measurements of quantum computers need attention." "A key area that deserves focus is the development of application and performance benchmarks that enable the comparison and evaluation of different technological implications of quantum computing."

218 "Due to the proliferation and evolution of multiple hardware platforms for quantum computing, it is too early to develop standards for many aspects of this technology." ""Custom connections needed for one company's system will not necessarily be relevant for other technical approaches."

219 "There is a need for skilled labour in the field of quantum technologies. More than half of quantum companies are currently hiring. These companies struggle to find people with the right skills for new positions in the emerging quantum job market. Some have referred to this as the 'quantum skills shortage.'"

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220 “If used on a general-purpose scalable quantum computer (that does not exist yet), [Shor’s algorithm] would break the encryption of today’s digital communications, compromising existing public-key cryptographic algorithms.” “None of the three methods [PQC, QRNG, QKD] is a silver bullet able to provide guaranteed protection from break-ins in the new quantum computing era.”

221 “Quantum computers… could transform the way the climate, food and energy security, and health are managed.” “Discovery and design of new molecules and materials… drug design, crops and fertilizers, green hydrogen catalysts, batteries, chemistry.”

222 “Even though today’s imperfect quantum computers… can already be accessed for research, pilots and business use case assessments.”

223 “There are actionable approaches for businesses… post-quantum cryptography… quantum random number generators… quantum key distribution.”

224 “A key area that deserves focus is the development of application and performance benchmarks… differences in underlying performance, changes in connectivity and eventual changes in error correcting codes.”

225 “More businesses need to understand the implications of quantum computing on their industry and formulate a quantum computing strategy.”

226 “Governments, businesses and research organizations have the potential to accelerate technology development for common good – if they work together.”

227 “Quantum computers… allow industries to potentially augment their optimization and machine learning processes to find new insights and make better and more precise decisions.” “Optimizing international shipping and delivery routes… improving real-time customer credit scoring.”

228 “Quantum computing is expected to accelerate machine learning algorithms… opening doors for smaller firms to train complex models theoretically at a fraction of the time and cost.”

229 https://www.ibm.com/roadmaps/quantum.pdf

230 “AI-enhanced circuit transpilation” refers to the use of AI to optimize quantum circuits to automatically transform high-level quantum programs into shorter, more efficient gate-level instructions that improve performance on quantum hardware. (https://www.ibm.com/quantum/blog/ai-transpiler-passes)

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233 https://www.etsi.org/newsroom/press-releases/2222-etsi-releases-world-first-protection-profile-for-quantum-key-distribution

234 https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q05_quantumtechnologiesusecases_release1.pdf

235 https://www.ibm.com/quantum/blog/circuit-layer-operations-per-second

236 https://www.ibm.com/quantum/blog/quantum-metric-layer-fidelity

237 “A prominent outcome… was the recognition that the IEEE can support defining, developing, and curating metrics and benchmarks for quantum computers. Attendees proposed the following framework… designed to capture the broadest definitions of quantum computing and to permit extension and refinement as new advances appear.” (https://rebootingcomputing.ieee.org/images/files/pdf/quantum/ieee-framework-for-metrics-and-benchmarks-of-quantum-computing.pdf)

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238 NIST is coordinating PQC migration guidelines. Their document notes gaps in application-specific security protocols. (https://nvlpubs.nist.gov/nistpubs/ir/2024/NIST.IR.8547.ipd.pdf)

239 ETSI ISG-QKD and ISO/IEC SC27 WG3 are developing Common Criteria Protection Profiles and security evaluation methods for QKD. (https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q05_quantumtechnologiesusecases_release1.pdf)

240 https://www.iso.org/standard/77097.html

241 "Comments received on this draft will be used to revise this transition plan and feed into other algorithm- and application-specific guidance for the transition to PQC." (https://csrc.nist.gov/pubs/ir/8547/ipd)

242 "A standard for the characterization of typical optical components of a QKD system has been published. Currently (beginning of 2022) a standardized ISO/EN 15408 'Common Criteria' (CC) Protection Profile (PP) for a QKD link is about to be finished. It is not clear whether that paradigmatic PP will actually be certified (or 'certifiable') as several base standards are still missing, or in an insufficient state." (https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q06_standardizationroadmapquantumtechnologies_release1-1.pdf)

243 "ISO/IEC 23837 (all parts) specifies security functional and assurance requirements also for QKD transmitter modules (also called 'sources'), as well as receiver modules ('detectors')." (https://www.iso.org/obp/ui/)

244 "There are technologies which are not (yet) covered in the existing standards. For these, additional standards may be required." (https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q04_standardizationroadmapquantumtechnologies_release1.pdf)

245 https://www.itu.int/dms_pub/itu-t/opb/fg/T-FG-QIT4N-2021-D2.5-PDF-E.pdf

246 "The QKD modules in the quantum layer had to be integrated with other encryption techniques in the communication layer to support an application in the health sector that requires a high level and long-term security… First, we designed (by referencing the ETSI and ITU-T standards) the interface and connection structure of QKD-KMS-transmission and exchange equipment." "The flexibility of the KMS makes it an extremely promising framework for integrating conventional cryptography, PQC algorithms… QKD systems able to manage and distribute keys among a network in a secure way and other encryption techniques like Homomorphic encryption…" (https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q05_quantumtechnologiesusecases_release1.pdf)

247 "QKDN providers also actively participate in QKD-related standardization work in SDOs. For example, CAS Quantum Network, as well as SK Telecom and KT Corporation promote standardization of QKDN architecture, functional requirements, and other projects in ITU-T SG13 and SG17." (https://www.itu.int/en/ITU-T/focusgroups/qit4n/Documents/D2.5.pdf)

248 https://www.etsi.org/deliver/etsi_gs/QKD/001_099/011/01.01.01_60/gs_QKD011v010101p.pdf

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[267] "The commercialization of quantum information technologies creates a nexus of many competing interests and concerns: unbridled enthusiasm, great science and engineering, people development and deficiencies, international cooperation and security, the need and risks of a global supply chain. Part of the National Quantum Coordination Office's job is to engage with the private sector and understand these issues." (https://www.quantum.gov/quantum-industry-and-society/)

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