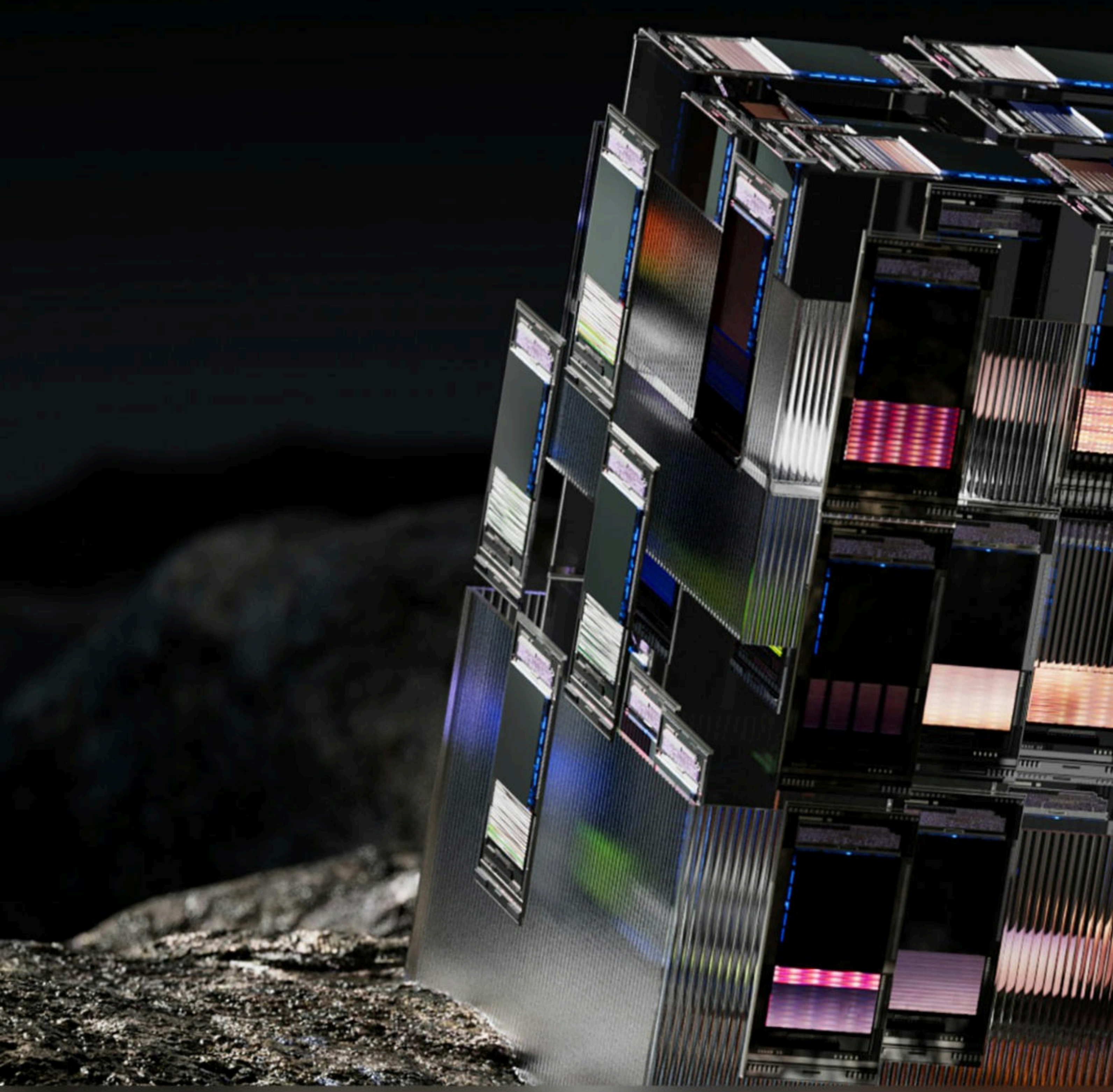
Quantum Computing - State of Play 2025

Global Landscape and the Convergence With Emerging Technologies



Quranium

December 31, 2025

Note from the CEO

Over the past two years, I have had the opportunity to engage in deep conversations across boardrooms, research laboratories, government corridors, and policy forums around the world. Despite the diversity of perspectives, one fundamental question continues to surface:

"Where are we, really, with quantum computing - and what does this mean for the systems we depend on today?"

This report has been written to answer that question with clarity and discipline. It deliberately avoids hype and alarmism, offering instead a realistic assessment of the progress being made across quantum hardware, error correction, cryptographic impact, and national strategy. Quantum computing is no longer a distant scientific curiosity; it is advancing along measurable trajectories that compel organizations to reassess the assumptions underlying their digital infrastructure and long-term security models.

The transition now underway is not abrupt, but it is structural. Decisions made in the present about cryptography, data durability, system architecture, and regulatory readiness - will determine whether institutions are leading the next era of computation or exposed by it.

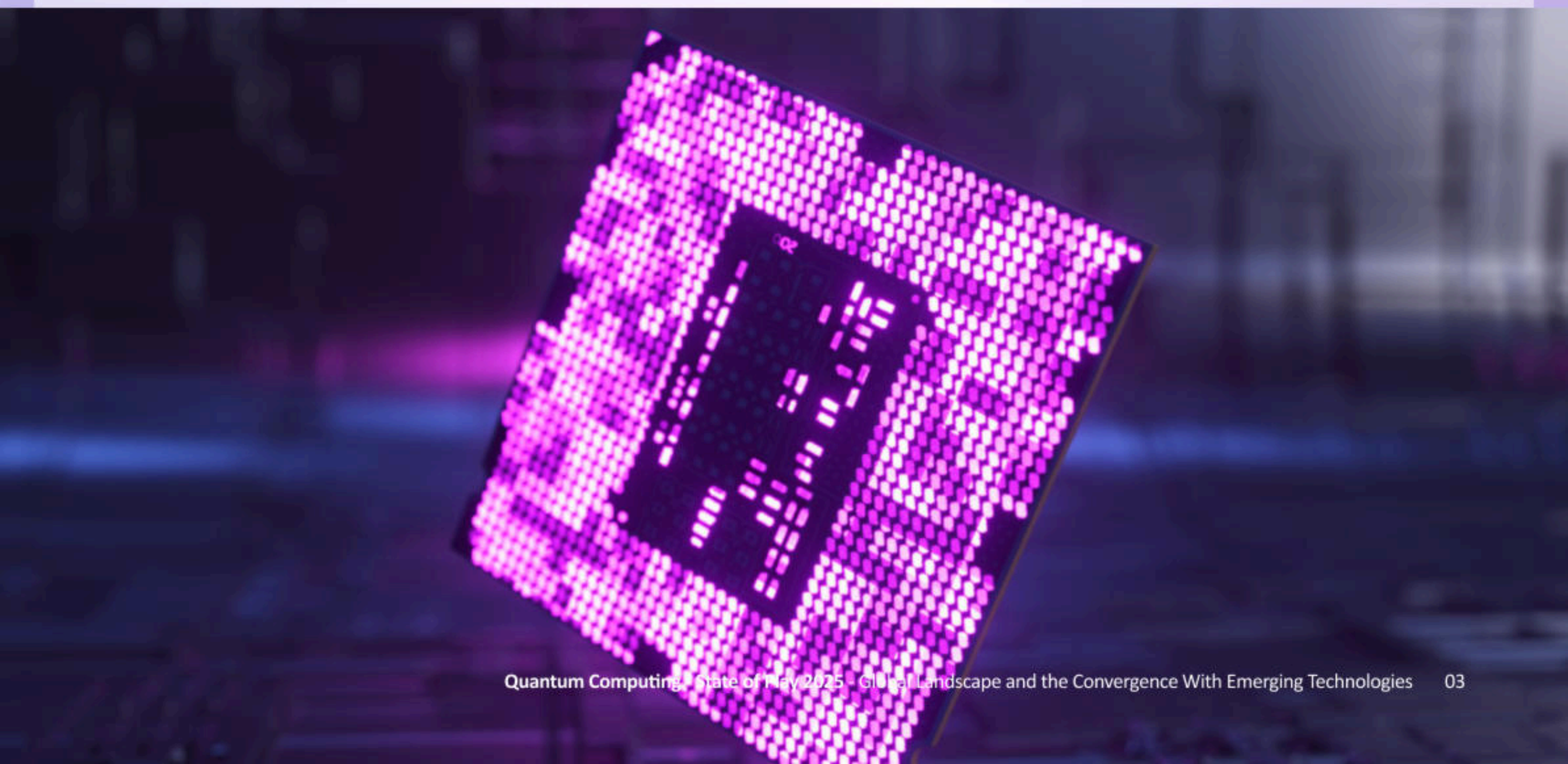
The purpose of this paper is to provide business leaders, technical teams, and policymakers with a clear and practical understanding of the transition now underway. It contextualizes current quantum capabilities, distinguishes near-term reality from long-term potential, and outlines the strategic direction in which governments, enterprises, and broader ecosystems are moving.

The quantum future will not arrive all at once, but its consequences will be permanent. Those who prepare with clarity today will define stability and trust in the decades to come.

Kapil Dhiman
CEO and Co-founder
Quranium

Table of Contents

Table of Contents



Executive Summary

Quantum computing has moved from speculative research to a strategic infrastructure transition. The momentum is now sufficient for governments, institutions, and major technology firms to treat quantum computing as a practical strategic priority. Hardware performance is improving, coherence is stabilising, and multiple chip architectures are being developed with credible pathways to scale. The question facing institutions today is no longer if quantum will matter, but how prepared they are for its arrival.

The period between 2025 and 2030 is emerging as a defining readiness window. During this phase, advances in hardware stability, error correction, and hybrid integration are converging with geopolitical competition and regulatory attention. Governments, research institutions, and major technology firms across the United States, China, Europe, Japan, Singapore, and the Middle East are expanding quantum initiatives that have shifted from exploratory programs to long-term strategic commitments. This alignment marks a transition from theoretical promise toward applied impact.

Progress is visible across every major hardware pathway, including superconducting qubits, trapped ions, photonic platforms, and neutral-atom systems. Each approach has matured along distinct trajectories over the past decade. Error correction, long regarded as the central bottleneck, is advancing through AI-driven techniques and new chip designs that improve stability and suppress noise. Early indicators of fault-tolerant architectures are now emerging.

These advances are beginning to reshape the broader compute stack. Classical processors will continue to underpin general-purpose computing. GPUs will expand their role as the engine of large-scale AI and high-performance workloads. Quantum systems are joining this landscape as a specialised layer, targeting problem classes that exceed classical limits, including simulation, optimisation, advanced cryptography, and scientific discovery. In parallel, quantum progress is reshaping expectations around digital security, accelerating the transition toward post-quantum cryptography and long-term resilience.

For leaders, the next 24-36 months are going to be the beginning for deployment and readiness. This means moving from passive monitoring to structured experimentation through hybrid quantum - classical pilots, cloud-based access, and domain-specific use cases. Attention should focus on error-correction progress, hybrid integration with classical compute, and institutional use cases where value is already measurable, rather than headline qubit counts, speculative consumer timelines, or assumptions of single-vendor dominance. At the same time, quantum risk can no longer be deferred: post-quantum cryptography is becoming a mandatory transition for systems involving long-lived data or value. While the transition will be gradual, its consequences for computation, security, and technological advantage will be structural and enduring.

1. Do Quantum Computers Exist Today?

1.1 The Basics

What is a Quantum Computer?

A quantum computer is a new class of computer that processes information using the principles of quantum physics, rather than the classical physics that underpins today's computers.

Classical vs Quantum - the core difference

Classical computers use bits that are either 0 or 1. Every calculation is built from long sequences of these binary decisions. Quantum computers use qubits, which can exist in a state of 0 and 1 at the same time - a property known as superposition.

This seemingly small difference fundamentally changes how computation works.

The three quantum properties that matter:

(i) Superposition: A qubit can represent multiple possibilities simultaneously. This allows a quantum computer to explore many computational paths in parallel.

(ii) Entanglement: Qubits can become linked such that the state of one instantly influences another, regardless of distance. This enables coordinated computation across many qubits, something classical systems cannot replicate.

(iii) Quantum interference: Quantum algorithms amplify correct outcomes and cancel incorrect ones through wave-like interference, making certain problems dramatically faster to solve.

Quantum algorithms amplify correct outcomes and cancel incorrect ones through wave-like interference, making certain problems dramatically faster to solve

What quantum computers are good at?

- Breaking or weakening classical cryptography
- Simulating molecules, materials, and chemical reactions
- Optimizing complex systems (logistics, finance, energy grids)
- Accelerating certain AI and machine-learning tasks

Why are quantum computers hard to build?

Quantum states are extremely fragile. Qubits must be isolated from noise, vibration, heat, and radiation - often requiring:

- Temperatures close to absolute zero
- Sophisticated error correction
- Massive engineering overhead for a relatively small number of usable qubits

In short, a quantum computer is not simply a faster computer. It is a fundamentally different way of computing. This is why today's quantum computers are large and expensive.

This is why today's quantum computers are large and expensive, and why those constraints are now being systematically engineered away. Before examining individual quantum-computing architectures, it is important to reset how progress in this field should be interpreted. Quantum computing does not advance along a single axis. Unlike the classical systems, where performance improvements can be tracked through familiar metrics such as clock speed, transistor density, or standardized benchmarks, quantum progress is multi-dimensional. There is no dominant architecture, no universally accepted success metric, and no single vendor setting the pace for this. Instead, progress is emerging through parallel development across multiple hardware approaches, each addressing different constraints and trade-offs.

At this stage, qubit count alone is an incomplete and often misleading indicator of capability. System quality is equally shaped by factors such as coherence time, gate fidelity, error behaviour, connectivity, and the ability to integrate with classical computing infrastructure. In many cases, smaller systems with higher stability and lower error rates are more practically useful than larger but noisier machines. This diversity in design choices reflects deliberate engineering strategy rather than fragmentation.

As a result, the current quantum landscape should be understood as an ecosystem rather than a race with a single winner. Superconducting circuits, trapped ions, photonic platforms, neutral atoms, silicon-spin devices, and emerging topological approaches are all progressing in parallel. Each is optimized for different problem classes, scaling pathways, and timelines to fault tolerance. This plurality increases the likelihood that quantum computing will mature not as a monolithic technology, but as a layered capability embedded within the broader compute stack.

For senior and non-technical readers, it is neither necessary nor expected to track every architectural detail that follows. What matters is the direction of travel. Hardware stability is improving. Error rates are declining. Cloud access is expanding. And systems are transitioning from laboratory experiments toward usable, hybrid infrastructure that institutions can begin to engage with today. The sections that follow provide a structured overview of the major hardware pathways shaping this transition. They are intended to clarify strategic intent, maturity, and long-term relevance - rather than to suggest that any single architecture has already emerged as definitive.

How to Read the Hardware Landscape

Progress in quantum computing should not be interpreted through a single metric or dominant architecture. Qubit count alone is an incomplete indicator of capability. System quality, measured by stability, error rates, coherence, connectivity, and integration with classical infrastructure, is equally decisive. As a result, multiple hardware approaches are advancing in parallel, each optimized for different trade-offs and timelines to fault tolerance.

At a high level, the principal hardware pathways can be understood as follows:

Superconducting circuits use cryogenically cooled electrical circuits to perform quantum operations at very high speed, making them the leading approach for near-term scaling and industrial manufacturing.

Trapped ions manipulate individual atoms suspended in electromagnetic fields, delivering exceptionally high precision and stability, which makes them well suited for error-corrected computation and scientific accuracy.

Photonic platforms encode quantum information in particles of light, enabling room-temperature operation and natural compatibility with optical networks, positioning them for long-term scalability and distributed quantum systems.

Neutral atoms arrange laser-controlled atoms in highly regular arrays, offering a balance between scalability and coherence that is attractive for large-scale simulation and optimisation problems.

Silicon-spin devices control the spin of electrons in silicon, allowing quantum chips to be fabricated using conventional semiconductor processes, which could dramatically accelerate manufacturability if key technical challenges are resolved.

Topological approaches aim to store quantum information in exotic physical states that are inherently protected from noise, representing a high-risk but potentially transformative path toward fault-tolerant quantum computing.

It is not necessary to track every architectural detail that follows. What matters is the direction of travel: hardware stability is improving, error rates are declining, and quantum systems are transitioning from experimental machines toward usable, hybrid infrastructure embedded within the broader compute stack.

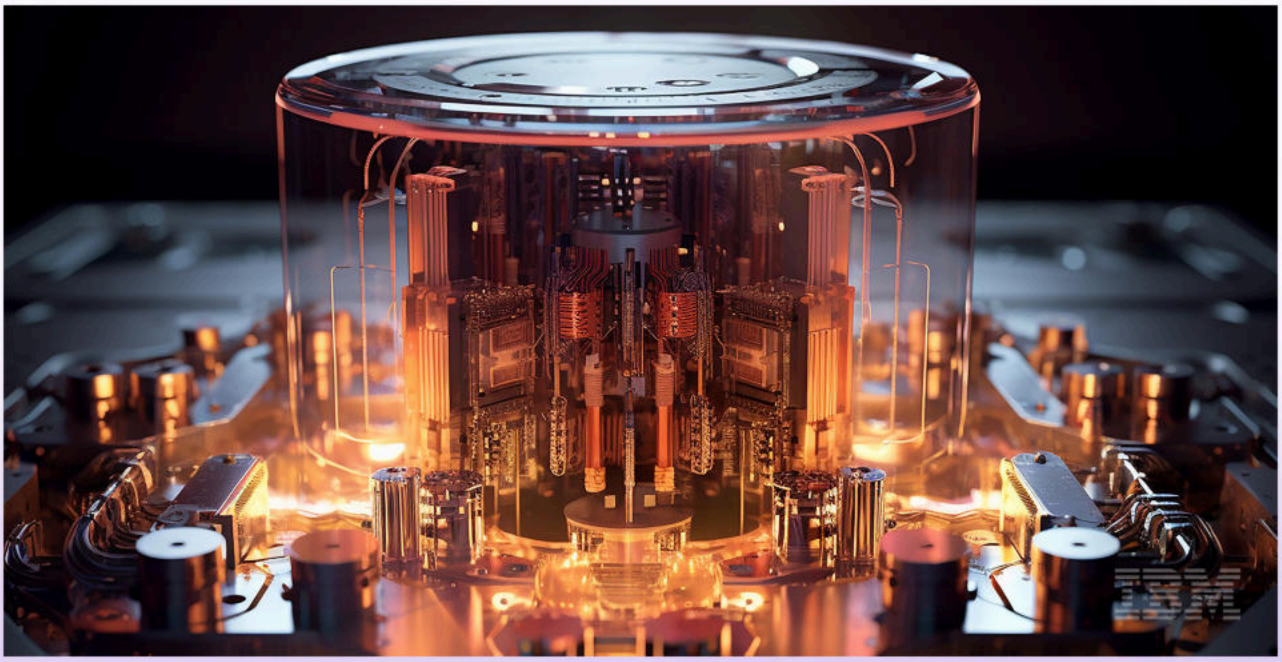
1.2 An Ecosystem of Hardware Builders

Superconducting Leaders - The Industrial Powerhouses

Superconducting quantum computing uses microwave-controlled circuits cooled near absolute zero, where electrical resistance vanishes and quantum states can form across engineered Josephson junctions. This approach enables fast gate speeds and industrial-scale chip fabrication, making it the leading architecture for large-scale quantum manufacturing.

IBM

IBM remains one of the most influential players in the quantum landscape, supported by a clear public roadmap and a fleet of systems available through their cloud. Their recent work centers on improving coherence, connectivity, and overall system quality instead of chasing qubit counts. The 133-qubit Heron processor is a key milestone from 2024, built around lower error rates and more consistent performance, and it forms the foundation of IBM's modular System Two architecture. While the 1,121-qubit Condor chip demonstrated that large-scale fabrication is possible, IBM's strategy now focuses on linking multiple high-fidelity Heron-class processors[1]. In 2025, the company introduced Nighthawk, a 120-qubit device capable of executing deeper circuits - up to 5,000 gates - through the IBM Quantum Platform. Their long-term ambition is a fully fault-tolerant system, code-named Starling, targeted for the end of the decade[2].



Source: How IBM Will Build The World's First Large-Scale, Fault-Tolerant Quantum Computer

[1] Post-Quantum (2025) IBM Quantum Computing. Available at: https://postquantum.com/quantum-computing-companies/ibm/

[2] IBM (2025) IBM Quantum Roadmap 2025. Available at: https://www.ibm.com/roadmaps/quantum/2025/

IBM's superconducting-qubit strategy is built around fabrication scalability and tight integration with established semiconductor manufacturing. Superconducting transmon qubits can be patterned on 300 mm wafers using advanced CMOS-compatible lithography, allowing IBM and its partners to iterate on coherence, connectivity, and uniformity at industrial scale[3]. This manufacturing base supports IBM's global deployment model, where quantum systems are increasingly co-located with high-performance computing infrastructure to enable hybrid quantum–classical workloads[4]. IBM has also built one of the world's largest quantum ecosystems, with the company reporting roughly $1 billion in cumulative quantum business since 2017 and committing substantial additional investment to quantum-centric supercomputing and U.S. manufacturing capacity[5]. Taken together, manufacturability at wafer scale, integration with classical HPC, and a growing commercial ecosystem distinguish IBM's superconducting approach within the broader quantum landscape.

IBM's quantum systems have been used for a range of practical experiments, including error-mitigated molecule simulations such as H_2 and LiH on Heron-class processors, demonstrating significantly improved stability and accuracy compared to earlier generations[6]. Researchers have also executed hybrid quantum-classical materials studies, including band-gap calculations for periodic materials using IBM hardware and Qiskit workflows, marking early signs of reliable scientific computation on mid-scale devices[7].

All of IBM's processors, from public devices to Heron and Nighthawk are accessible today through the IBM Quantum Platform, where users can run circuits directly via cloud APIs and Qiskit[8]. This infrastructure is now being used to prototype real-world workloads in materials discovery, drug modelling, supply-chain optimization, financial portfolio research, and algorithm development, areas broadly recognised by IBM as early targets for quantum advantage once fault-tolerant systems arrive[9].

[3] IBM (2025) 300 mm Fab for Quantum Chips. Available at: https://www.ibm.com/quantum/blog/300mm-fab

[4] IBM. Quantum-centric Supercomputing. Available at: https://www.ibm.com/think/topics/quantum-centric-supercomputing

[5] IoT World Today (2025) IBM Reports $1B in Cumulative Quantum Computing Revenue. Available at: https://www.iotworldtoday.com/quantum/ibm-reports-1b-in-cumulative-quantum-computing-revenue

[6] AbuGhanem, M. (2025) IBM quantum computers: evolution, performance, and future directions. The Journal of Supercomputing, 81, article 687. Available at: https://link.springer.com/article/10.1007/s11227-025-07047-7

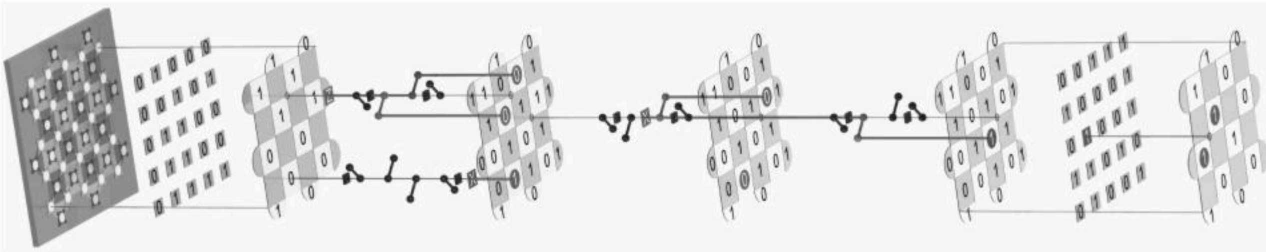
[7] IBM (2025) Hybrid quantum-classical simulation of periodic materials. Available at: https://research.ibm.com/publications/hybrid-quantum-classical-simulation-of-periodic-materials

[8] IBM (2025) IBM Quantum Cloud. Available at: https://quantum.cloud.ibm.com/

[9] IBM (2025) Quantum computing. Available at: https://www.ibm.com/think/topics/quantum-computing

Google

Google Quantum AI is the other gravitational center of the superconducting ecosystem, defined less by product cadence and cloud access and more by its uncompromising pursuit of long-horizon fault tolerance. By 2025, Google had solidified a roadmap built around deep hardware purity, aggressive control engineering, and algorithmic correctness, a philosophy designed to solve the fault-tolerance problem before addressing commercial workloads. Many researchers describe this posture as Google's defining signature: a willingness to prioritise long-term scientific milestones over near-term utility. Unlike players optimising for incremental capability, Google is aiming directly at the first fully fault-tolerant quantum computer, irrespective of timeline, tooling, or cost.



Source: [Making Quantum Error Correction Work]

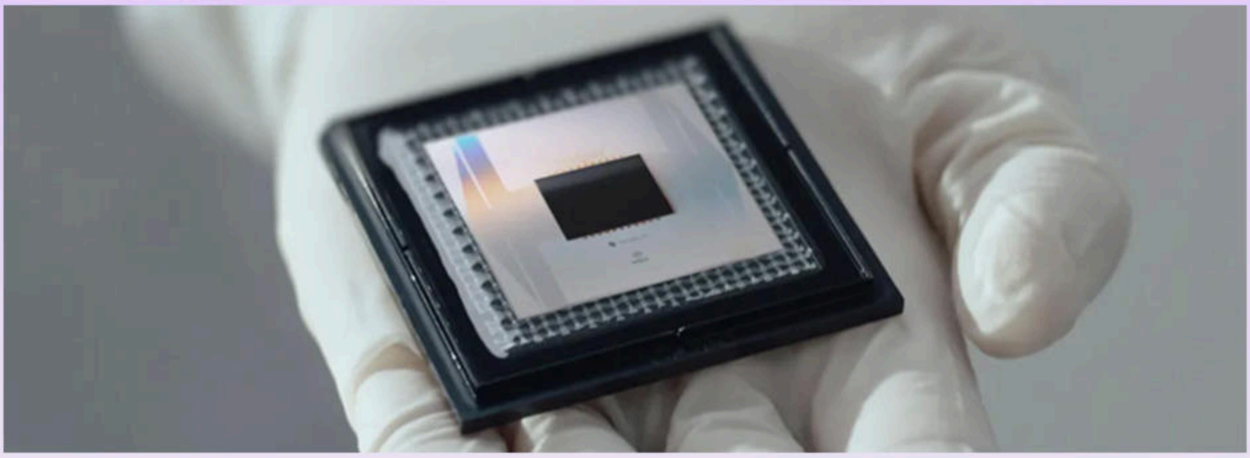
Google Quantum AI also stands as one of the most prominent forces in the field, with a strategy that leans heavily toward pushing the boundaries of error correction[10]. Their 2025 hardware work is anchored by the Willow processor, built to support deeper experiments in stabilizing logical qubits. Google's most important milestone in this period is the demonstration that expanding the number of physical qubits within a surface-code architecture can meaningfully suppress logical error rates[11]. It is the first clear validation that scaling the code actually improves reliability, which is an essential proof point for any path toward fault tolerance[12]. Larger, higher-quality arrays of qubits can create logical units stable enough to support practical computation[13].

[10] Google Quantum AI (2024) Our quantum error correction milestone. Available at: https://quantumai.google/qecmilestone

[11] Google Research (2024) Making quantum error correction work. Available at:
https://research.google/blog/making-quantum-error-correction-work/

[12] Google DeepMind / Google Quantum AI (2024) AlphaQubit tackles one of quantum computing's biggest challenges. Available at:
https://blog.google/technology/google-deepmind/alphaqubit-quantum-error-correction/

[13] Post-Quantum (2023) Google Claims Breakthrough in Quantum Error Correction. Available at:
https://postquantum.com/quantum-research/google-breakthrough-error-correction/



In parallel, Google introduced the Quantum Echoes algorithm in 2025. A system-level diagnostic that demonstrated verifiable quantum advantage on physically relevant problems, marking a critical step toward translating fault-tolerant progress into real-world applications in chemistry, materials science, and complex physical systems. Google said it has developed a computer algorithm that points the way to practical applications for quantum computing and will be able to generate unique data for use with artificial intelligence. The new algorithm which runs on the company's quantum chip, is 13,000 times faster than the most sophisticated classical computing algorithm on supercomputers[14].

Google has conducted some of the most significant experiments in the field, including the 2019 "quantum supremacy" demonstration on the 53-qubit Sycamore processor, which executed a sampling task far beyond classical capability[15]. Its most important recent achievement is the 2023 validation that scaling a surface-code logical qubit from 17 to 49 physical qubits can reduce logical error rates[16], offering the clearest experimental evidence yet that larger codes can improve reliability, which is a foundational requirement for fault tolerance[17]. Unlike IBM, whose hardware is openly available via cloud queues, Google's quantum systems are not directly accessible to the general public. Instead, developers interact through Cirq and TensorFlow Quantum, while full hardware access is reserved for select academic and industry collaborations . Cirq and TensorFlow Quantum are Google's software frameworks for designing and simulating quantum circuits, but they do not provide direct access to Google's quantum hardware, meaning the public can build algorithms, yet cannot run them on Google's machines without being part of a formal research collaboration.

[14] Google (2025) Our Quantum Echoes algorithm is a big step toward real-world applications for quantum computing. Available at: https://blog.google/technology/research/quantum-echoes-willow-verifiable-quantum-advantage/
[15] Arute, F. et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature. Available at: https://www.nature.com/articles/s41586-019-1666-5
[16] Google Quantum AI (2023) Suppressing quantum errors by scaling a surface code logical qubit. Nature. Available at: https://www.nature.com/articles/s41586-022-05434-1
[17] Google Quantum AI (2023) Suppressing quantum errors by scaling a surface code logical qubit. Available at: https://research.google/blog/suppressing-quantum-errors-by-scaling-a-surface-code-logical-qubit/
[18] Google Quantum AI (2025) Google Quantum AI. Available at: https://quantumai.google/

These tools are used today for algorithm research, quantum simulation, optimization studies, and advanced error-correction experiments, which are areas that will become practical once stable logical qubits are achieved. Google's total investment in quantum computing is not publicly disclosed, but several verifiable funding activities provide a sense of the scale at which the company is operating. In 2025, Google participated in SandboxAQ's $150 million funding round, reinforcing its support for quantum-AI and post-quantum cybersecurity technologies[19] . That same year, Google Quantum AI also took part in a $230 million financing round for QuEra Computing, one of the leading neutral-atom quantum hardware companies[20]. Although the company has not published the cost of its internal hardware developments, Google's processors, such as Sycamore and Willow, represent multi-year R&D commitments involving dedicated fabrication facilities, specialized teams, and large-scale experimental programs, signalling investment far beyond these publicly visible figures.

rigetti

While smaller than IBM and Google, Rigetti's superconducting strategy is more accessible and enterprise-focused. Rigetti Computing is one of the early full-stack pioneers in the quantum ecosystem, with a focus on building systems that integrate hardware, software, and cloud access. Their 84-qubit Ankaa-3 system, released in late 2024, marked real progress by reaching a median two-qubit gate fidelity of 99.5%, which is a meaningful step toward more stable computation. Through 2025, the company has concentrated on lowering error rates and improving overall system performance, with a new machine exceeding 100 qubits expected by the end of 2025. Rigetti's processors are available through its own cloud platform and are also integrated into AWS Braket and Microsoft Azure, giving developers broad access to their technology[21].

Rigetti's systems are among the most accessible in the superconducting quantum-computing ecosystem. Its quantum processors are available through its own platform and via major cloud-providers such as Amazon Braket and Microsoft Azure Quantum, which enables developers and enterprises worldwide to run real quantum circuits without owning a physical machine[22]. These machines are actively used for hybrid quantum–classical workflows: quantum simulation, combinatorial optimization, machine-learning experiments, and early error-mitigation studies, concrete applications that illustrate how quantum can deliver practical value today[23].

[19] Reuters (2025) AI startup SandboxAQ adds NVIDIA, Google as backers, raises additional $150 million. Available at: https://www.reuters.com/technology/artificial-intelligence/ai-startup-sandboxaq-adds-NVIDIA-google-backers-raises-additional-150-million-2025-04-04/

[20] Reuters (2025) Quantum-computing startup QuEra closes US$230 million funding round. Available at: https://www.reuters.com/technology/quantum-computing-startup-quera-closes-230-million-funding-round-2025-02-11/

[21] Rigetti Computing (2024) Rigetti Computing launches 84-Qubit Ankaa™-3 System; achieves 99.5% median two-qubit gate fidelity milestone. Available at: https://www.globenewswire.com/news-release/2024/12/23/3001239/0/en/Rigetti-Computing-Launches-84-Qubit-Ankaa-3-System-Achieves-99-5-Median-Two-Qubit-Gate-Fidelity-Milestone.html

[22] AWS. Rigetti – Amazon Braket Quantum Computers. Available at: https://aws.amazon.com/braket/quantum-computers/rigetti/

[23] Rigetti Computing. Applications. Available at: https://www.rigetti.com/applications

In early 2025, Rigetti announced a major capital raise, approximately $153.3 million from a direct offering, and secured a strategic collaboration with server-hardware leader Quanta Computer, under which both parties committed over $100 million toward joint development of scalable superconducting quantum systems[24]. This level of funding, combined with broad cloud distribution and a clear enterprise-oriented roadmap, positions Rigetti as one of the few players building quantum infrastructure strictly for near-term practical use, rather than purely long-term research.

FUJITSU & RIKEN

Fujitsu and RIKEN recently unveiled a 256-qubit superconducting quantum computer, available via the "RQC-Fujitsu" hybrid quantum platform - making it one of the most powerful externally usable machines in 2025._The system is offered to global companies and research institutions, not just in Japan, which means researchers worldwide can (in principle) access it for advanced experiments[25].

The 256-qubit machine significantly expands the scope of quantum-classical hybrid workloads: Fujitsu and RIKEN highlight applications in molecular and materials simulation, complex chemistry, and error-correction algorithm testing as early use cases, leveraging the increased qubit count and improved architecture to tackle larger molecules and more sophisticated quantum algorithms[26].The project is backed by Japan's national quantum technology effort, part of a broader strategy that aims for a 10,000+ qubit superconducting quantum computer by 2030 under national funding and industrial-scale R&D programs[27]. This level of government and institutional commitment positions Fujitsu + RIKEN as a major global player, not just in hardware scale, but in making quantum computing accessible and oriented toward real-world industry and scientific challenges.

CTQG & 国盾量子 QuantumCTek

The Zuchongzhi research group, set up by a team from the China Telecom Quantum Group (CTQG) and QuantumCTek Co Ltd, has cemented China's position among global superconducting-quantum leaders with its 2025 launch of Zuchongzhi 3.0, a 105-qubit superconducting processor that demonstrated state-of-the-art performance and computational-advantage benchmarks[28].

[24] Rigetti Computing (2025) Rigetti Computing Reports Fourth Quarter and Full-Year 2024 Results. Available at: Zomputing-reports-fourth-quarter-and-full-year-2024

[25] Fujitsu (2025) Fujitsu and RIKEN develop world-leading 256-qubit superconducting quantum computer. Available at: https://www.fujitsu.com/global/about/resources/news/press-releases/2025/0422-01.html

[26] RIKEN (2025) RIKEN and Fujitsu unveil world-leading 256-qubit quantum computer. Available at: https://www.riken.jp/en/news_pubs/news/2025/20250422_1/index.html

[27] DataCenterDynamics (2025) Fujitsu begins development of 10,000-plus qubit quantum computer. Available at: https://www.datacenterdynamics.com/en/news/fujitsu-begins-development-of-10000-plus-qubit-quantum-computer/

[28] China State Council (2025) China hits new landmark in global quantum computing race. Available at: https://english.www.gov.cn/news/202503/04/content_WS67c656dbc6d0868f4e8f0489.html

Zuchongzhi 3.0 is available via the Tianyan quantum cloud, a public quantum-cloud platform run by CTQG, which as of late 2025 reportedly hosts aggregated access from users worldwide. The system has executed more than 2 million experiments for users in over 60 countries, making it among the largest open-access quantum-cloud infrastructures globally[29]. Through Tianyan, global researchers and institutions can run real quantum circuits, enabling applications in random-circuit sampling (benchmarking and supremacy tasks), prototype quantum-algorithm development, quantum-simulation research (e.g., materials or noise modeling), and early error-mitigation experiments. These use cases align with those explored internationally by other quantum-cloud services. In terms of funding, while CTQG and China's broader quantum program are publicly supported under national strategic initiatives, CTQG has not published a consolidated budget or total-investment figure for Zuchongzhi 3.0 or the Tianyan platform. Public reporting focuses on milestones (qubit count, performance metrics, cloud-access launch) rather than financial disclosure.

That said, the speed of development, the public-cloud deployment, and the scale of user outreach suggest considerable institutional commitment. Zuchongzhi 3.0 achieves high fidelity: single-qubit gates at ~99.90%, two-qubit gates at ~99.62%, and readout fidelity at ~99.13%.[30] These performance characteristics, along with a 32-cycle, 83-qubit random-circuit sampling experiment producing 1 million samples in a matter of minutes, establish a superconducting-system benchmark that few others currently match[31]. Building on this platform, the Zuchongzhi research group has demonstrated fault-tolerant quantum error correction below the surface-code threshold on a 107-qubit superconducting processor, using an all-microwave control approach. Reported in Physical Review Letters in 2025, the result marks the first below-threshold surface-code demonstration outside the United States and places China alongside Google at the leading edge of scalable quantum error correction. Using the Zuchongzhi 3.2 system, the team achieved stable distance-7 surface-code performance, with logical error rates decreasing as code distance increased, a defining criterion for fault-tolerant operation.

The work's distinguishing feature is its treatment of leakage errors, a major obstacle in superconducting systems. Rather than relying on additional hardware channels or direct-current control, the researchers implemented a purely microwave-based leakage-suppression scheme, using shaped pulses to confine qubits to their computational subspace and to reset ancilla qubits during repeated error-correction cycles. The system exhibited an error-suppression factor of approximately 1.4, confirming operation below the fault-tolerance threshold[32]. At the systems level, the microwave-only approach reduces wiring and layout complexity within cryogenic environments, where control-line density and thermal constraints increasingly limit scalability. Because microwave signals can be multiplexed, this strategy offers a more hardware-efficient pathway toward larger surface-code implementations while remaining compatible with existing superconducting control stacks. The result demonstrates that multiple architectural routes to fault-tolerant quantum computing are now viable, reinforcing the increasingly global and competitive nature of progress in the field.

Together, these superconducting efforts define the industrial, large-scale, fabrication-driven path to quantum.

[29] China Daily (2025) China's superconducting quantum computer ready for commercial use. Available at: https://global.chinadaily.com.cn/a/202510/12/WS68eb6e3aa310f735438b47fc.html

[30] University of Science and Technology of China (2025) Zuchongzhi-3: A 105-Qubit Superconducting Quantum Processor with 10^{15} Times Speedup in Circuit Sampling. Available at: https://en.ustc.edu.cn/info/1007/5015.htm

[31] APS Journals (2025) Establishing a New Benchmark in Quantum Computational Advantage with 105-qubit Zuchongzhi 3.0 Processor. Available at: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.134.090601

[32] Tan He et al., "Experimental Quantum Error Correction below the Surface Code Threshold via All-Microwave Leakage Suppression," Physical Review Letters 135, no. 26 (2025). Available at: https://doi.org/10.1103/rqkg-dw31

Quantum Annealing

D-Wave
The Quantum Computing Company™

D-Wave has pursued a distinct superconducting architecture based on quantum annealing while most superconducting quantum computing programs prioritize gate-based, universal quantum computation. This paradigm is optimized for solving large-scale combinatorial optimization and sampling problems rather than implementing arbitrary quantum circuits. As of 2025, D-Wave's flagship Advantage2 system comprises more than 4,400+ superconducting flux qubits, incorporating substantial advances in qubit connectivity, coherence, and noise suppression relative to prior generations. Instead of gate operations, problems are encoded directly into physical energy landscapes, allowing the system to converge toward optimal or near-optimal solutions via annealing dynamics. Advantage2 is publicly accessible today via D-Wave's Leap™ quantum cloud platform, and is also deployed in select on-premise and government environments, making it one of the most widely used quantum systems globally by real workload volume[33].

D-Wave's annealers are actively applied to production and pilot workloads, including logistics and supply-chain optimization, workforce scheduling, portfolio construction, materials science, and hybrid quantum–classical machine-learning solvers[34]. A defining characteristic of D-Wave's approach is its tight integration with classical CPUs and GPUs, where quantum hardware accelerates the hardest combinatorial sub-problems within larger hybrid solvers[35]. While quantum annealers are not universal quantum computers and are not designed for fault-tolerant algorithms such as Shor's, they represent the clearest example of recurring commercial quantum value at scale today[36]. Within the superconducting ecosystem, D-Wave therefore occupies a complementary position: demonstrating that specialized quantum architectures can deliver economically meaningful results years before fully fault-tolerant, gate-based systems mature.

Neutral Atoms

Pasqal

Pasqal illustrates how error correction is moving from proof points to deployable systems on neutral-atom hardware. Rather than optimizing for raw qubit count, Pasqal's roadmap is explicitly structured around scalable logical qubits, with 100+ qubit processors already deployed to end users and a clear path to error-aware, hardware-accelerated algorithms entering production by 2025. Its planned scale-up to a 10,000-qubit system by 2026 is framed as a QEC milestone as much as a hardware one, aimed at reducing effective error rates through architectural regularity, parallelism, and logical abstraction. The significance is not a single headline experiment, but the industrialization of error correction as a system capability, treating QEC as an operational layer rather than a laboratory exercise[37].

[33] D-Wave. Advantage2 System: Our Most Advanced and Performant Quantum Computer. Available at: https://www.dwavequantum.com/solutions-and-products/systems/
[34] D-Wave. Quantum Optimization. Available at: https://www.dwavequantum.com/solutions-and-products/quantum-optimization/quantum-optimization-landing-page/
[35] D-Wave (2020) D-Wave Hybrid Solver Service: An Overview. Available at: https://www.dwavequantum.com/media/4bnpi53x/14-1039a-b_d-wave_hybrid_solver_service_an_overview.pdf
[36] McGeoch (2020). Theory versus Practice in Annealing-Based Quantum Computing, Theoretical Computer Science, 816 (May 2020): 169–183. Available at: https://doi.org/10.1016/j.tcs.2020.01.024
[37] Pascal (2024) Pasqal announces New Roadmap focused on Business Utility and Scaling beyond 1,000 Qubits towards Fault Tolerance Era. Available at: https://www.pasqal.com/newsroom/pasqal-announces-new-roadmap-focused-on-business-utility-and-scaling-beyond-1000-qubits-towards-fault-tolerance-era/

Atom Computing has advanced within U.S. defense-led evaluation programs focused on near-term, utility-scale quantum systems. The company was selected by the Defense Advanced Research Projects Agency (DARPA) to progress to a subsequent phase of assessment examining whether its highly scalable neutral-atom architecture can support utility-scale quantum computing on accelerated timelines. Earlier in the year, DARPA included Atom Computing in Stage A of the Quantum Benchmarking Initiative, an expansion of the Underexplored Systems for Utility-Scale Quantum Computing program, designed to rigorously evaluate whether industrially useful quantum computers can be realized substantially sooner than conventional projections suggest.[38]

Trapped-Ion Leaders - The Fidelity Masters

Source: Quantinuum System Model H2 (Quantinuum, 2025)

Trapped-ion quantum computing works by levitating electrically charged atoms in electromagnetic fields and using lasers to manipulate their quantum states with extreme precision. Because every ion is identical and perfectly isolated, this method delivers the highest fidelities and most stable qubit behavior of any architecture today. If superconducting firms win through scale, trapped-ion companies win through precision.

QUANTINUUM

Quantinuum currently operates the world's highest-fidelity commercial quantum systems, led by its trapped-ion System Model H2, which as of September 2025 holds the record Quantum Volume of 225 = 33,554,432 – the highest reported system-level benchmark across any architecture and is additionally confirmed in Quantinuum's own technical glossary[39]. The Quantum Volume score of 33,554,432 means the system can reliably run quantum calculations that are over 33 million times more complex than the baseline test, making it the most capable quantum computer by this benchmark. This Quantum Volume record reflects simultaneous gains in stability, coherence, gate fidelity, and controllability across all 56 physical qubits in H2, and builds on earlier benchmarks such as achieving 99.9% two-qubit gate fidelity and running 14,000 logical-qubit experiments with Microsoft without a single detected error, an early demonstration of error-corrected behavior at useful scales[40].

[38] Atom Computing (2025) Atom Computing selected by DARPA for the next stage of exploring near-term utility-scale quantum computing with neutral atoms. Available at: https://atom-computing.com/atom-computing-selected-by-darpa-for-the-next-stage-of-exploring-near-term-utility-scale-quantum-computing-with-neutral-atoms/

[39]Quantum Computing Report (2025) Quantinuum Achieves Quantum Volume of 2^{25} on System Model H2. Available at: https://quantumcomputingreport.com/quantinuum-achieves-quantum-volume-of-2%C2%B2%E2%81%B5-on-system-model-h2/
Quantinuum (2025) Quantum Volume. Available at: https://www.quantinuum.com/glossary-item/quantum-volume

[40] Quantinuum (2025) Quantinuum extends its significant lead in quantum computing, achieving historic milestones for hardware fidelity and quantum volume. Available at: https://www.quantinuum.com/blog/quantinuum-extends-its-significant-lead-in-quantum-computing-achieving-historic-milestones-for-hardware-fidelity-and-quantum-volume
Quantinuum (2025) Quantinuum and Microsoft announce new era in quantum computing with breakthrough demonstration of reliable qubits. Available at: https://www.quantinuum.com/press-releases/quantinuum-and-microsoft-announce-new-era-in-quantum-computing-with-breakthrough-demonstration-of-reliable-qubits

Quantinuum's systems are accessible globally via cloud channels (including direct access to H-series hardware and high-fidelity emulators), and are already used in production-grade research for quantum chemistry, materials simulation, optimization, cybersecurity, and quantum-enhanced AI, including error-corrected chemistry workflows and industrial chemistry solvers developed with enterprise partners [41].

On the financial side, Honeywell and external investors have raised roughly $600–800 million in equity capital for Quantinuum at a $10 billion pre-money valuation, bringing total disclosed funding since inception to approximately $625 million prior to the latest round, one of the largest single capital commitments to any quantum-hardware company globally[42].

This combination of record system performance, error-corrected experimental milestones, broad cloud accessibility, and deep capital backing makes Quantinuum the reference point for high-fidelity trapped-ion quantum computing in the current NISQ era.

IONQ

IonQ is one of the leading trapped-ion quantum-computing companies and among the fastest-scaling firms in the field. In 2025, IonQ announced that its Tempo system reached a record algorithmic-qubit metric (#AQ) of 64, surpassing its previous targets and setting a new benchmark for practically relevant quantum performance [43]. IonQ's 2025 "accelerated roadmap", boosted by the acquisition of Oxford Ionics (for USD $1.075 billion) and its earlier acquisition of ID Quantique (IDQ), targets up to 2 million physical qubits, translating into ~40,000–80,000 logical qubits by 2030, with projected logical-error rates as low as 10^{-12}.[44]

Through the Oxford Ionics deal, IonQ gains access to novel "ion-trap-on-a-chip" technology, complementing its existing hardware stack and supporting scaling, higher fidelity, and improved unit economics[45]. Similarly, with ID Quantique, IonQ has expanded into quantum communication and secure-networking capabilities - embedding quantum-networking / quantum-cryptography into its long-term vision [46].

[41] Quantinuum (2025) Quantinuum System Model H2. Available at: https://www.quantinuum.com/products-solutions/quantinuum-systems/system-model-h2

[42] Reuters (2025) Honeywell's Quantinuum raises funds from NVIDIA, others at $10 billion valuation. Available at: https://www.reuters.com/business/honeywells-quantinuum-raises-funds-NVIDIA-others-10-billion-valuation-2025-09-04/

[43] IonQ (2025) IonQ Achieves Record-Breaking Quantum Performance Milestone of #AQ 64. Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Achieves-Record-Breaking-Quantum-Performance-Milestone-of-AQ-64/default.aspx

[44] PostQuantum (2025) IonQ's 2025 Roadmap: Toward a Cryptographically Relevant Quantum Computer by 2028. Available at: https://postquantum.com/industry-news/ionqroadmap-crqc/

[45] IonQ (2025) IonQ Completes Acquisition of Oxford Ionics, Rapidly Accelerating Its Quantum Computing Roadmap. Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Completes-Acquisition-of-Oxford-Ionics-Rapidly-Accelerating-Its-Quantum-Computing-Roadmap/default.aspx

[46] IonQ (2025) IonQ Completes Acquisition of ID Quantique, Cementing Leadership in Quantum Networking and Secure Communications. Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Completes-Acquisition-of-ID-Quantique-Cementing-Leadership-in-Quantum-Networking-and-Secure-Communications/default.aspx

IonQ claims that its systems are already being accessed via cloud / enterprise-grade channels, and it envisions use cases across drug discovery, materials science, optimization, encryption/quantum-safe communication, and large-scale modeling, once logical-qubit scaling and fault tolerance mature[47].

Financially and strategically, IonQ's aggressive acquisition-driven expansion, plus its patent portfolio and diversified quantum-tech stack (compute + networking + sensing), positions it as one of the most heavily resourced and forward-looking players in quantum computing today.

Trapped-ion machines have slower clocks than superconducting processors, but their quality makes them the architecture to watch for error-corrected chemistry, simulation, and cryptography which are areas highly relevant to institutional and scientific use cases.

Photonic Players - The Scalability Visionaries

Ψ PsiQuantum

PsiQuantum leads the photonic charge. Backed by over $1 billion in its 2025 Series E round, PsiQuantum has unveiled its photonic-chipset architecture, built on silicon-photonics and standard semiconductor manufacturing, explicitly targeting a million-qubit, fault-tolerant quantum computer[48]. The company aims to build full-scale "utility-grade" quantum machines by leveraging wafer-scale photonic chips, optical switches, and telecom-style networking to scale efficiently beyond small prototypes[49].

PsiQuantum has stated that the new funding will support prototype deployment, expansion of optical-switch production, and construction of major quantum-data-center-style facilities (in e.g. Brisbane and Chicago), a clear sign that they view their technology as a long-term infrastructure investment rather than a near-term lab experiment. As of 2025, the company is actively integrating its chips at scale and preparing cryogenic, rack-style cooling + networking systems[50].

[47] IonQ (2025) IonQ Advances to Stage B of DARPA's Quantum Benchmarking Initiative (QBI). Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Advances-to-Stage-B-of-DARPAs-Quantum-Benchmarking-Initiative-QBI/default.aspx

[48] PsiQuantum (2025) PsiQuantum Raises $1 B to Build Million-Qubit Scale, Fault-Tolerant Quantum Computers. Available at: https://www.psiquantum.com/news-import/psiquantum-1b-fundraise

[49] PsiQuantum (2025) PsiQuantum raises $1 billion in Series E funding — NVIDIA, BlackRock among backers. Available at: https://www.siliconrepublic.com/start-ups/psiquantum-1bn-raise-NVIDIA-blackrock-quantum-chips-manufacturing

[50] IEEE Spectrum (2025) PsiQuantum Plans Quantum Supercomputer That Runs on Light. Available at: https://spectrum.ieee.org/psiquantum-supercomputer

Xanadu, modular photonics + software + networking. In January 2025, Xanadu unveiled Aurora, described as a modular, networked photonic quantum computer built from 35 photonic chips interconnected with ~13 km of fiber optics, and operating at room temperature[51]. While Aurora itself is modest in qubit count (12 qubits in the announced system), the design is explicitly meant for scalability via optical networking and modular racks, enabling potential growth to far larger systems in the future[52].

Xanadu's value proposition differs from "build-the-million-qubit-machine" firms that it combines photonic hardware with open-source software tools, notably PennyLane, to let researchers and developers integrate photonic quantum computation into existing HPC / simulation / machine-learning workflows today. As of 2025, Aurora is operational, but like most photonic architectures, it remains in early-stage systems, useful for experimentation, research, and early applications.

In July 2025, BTQ Technologies announced a public demonstration of a quantum "Proof-of-Work" (Q-PoW) simulator using a photonic sampling approach, aimed at quantum-native mining simulations and future-proof blockchain systems. This suggests one of the earliest niche use-cases for photonic quantum computers outside of chemistry or optimization: cryptography, consensus algorithms, and blockchain workloads. As of now, BTQ's system is a simulator for research / proof-of-concept[53].

BTQ and ICTK announced a $15 million joint investment and development agreement to co-develop a quantum-secure secure-element chip known as Quantum Compute in Memory (QCIM) that integrates post-quantum cryptography and cryptographic acceleration at the silicon layer. The QCIM chip is designed to enable crypto-agile upgrades without altering customer workflows and is targeted for use cases including digital asset wallets, mobile authentication, payment systems, Internet of Things endpoints, defense systems, and critical infrastructure; early performance metrics indicate substantial improvements in encryption throughput and energy efficiency. The partnership leverages ICTK's secure-element manufacturing capabilities and distribution channels to pursue mass production, testing, and certification with engagement in international standards bodies to facilitate rapid adoption. This collaboration reflects a practical response to anticipated quantum computing threats by embedding quantum-safe security directly into hardware platforms[54].

[51] Xanadu (2025) Xanadu introduces Aurora: world's first scalable, networked and modular quantum computer. Available at: https://www.xanadu.ai/press/xanadu-introduces-aurora-worlds-first-scalable-networked-and-modular-quantum-computer
[52] Xanadu (2025) Xanadu unveils Aurora: the world's first scalable photonic quantum computer. Available at: https://www.innovationnewsnetwork.com/xanadu-unveils-aurora-the-worlds-first-scalable-photonic-quantum-computer/54880/
[53] Quantum Insider (2025). BTQ Launches Quantum Proof-of-Work Simulator, Delivering Demonstration of Quantum Advantage in Blockchain Consensus. Available at: https://thequantuminsider.com/2025/07/08/btq-launches-quantum-proof-of-work-simulator-delivering-demonstration-of-quantum-advantage-in-blockchain-consensus/
[54] QPR Newswire (2025) BTQ and ICTK Sign USD 15M Quantum-Secure Chip Development and Joint Investment Agreement to Advance Global Quantum-Safe Hardware. Available at: https://www.prnewswire.com/news-releases/btq-and-ictk-sign-usd-15m-quantum-secure-chip-development-and-joint-investment-agreement-to-advance-global-quantum-safe-hardware-302595200.html

Silicon-Spin & Topological - The Wildcards That Could Rewrite the Field

Silicon-spin and topological qubits represent two of the most unconventional bets in quantum computing, architectures that could unlock new scaling curves if their physics can be stabilized and manufactured at scale.

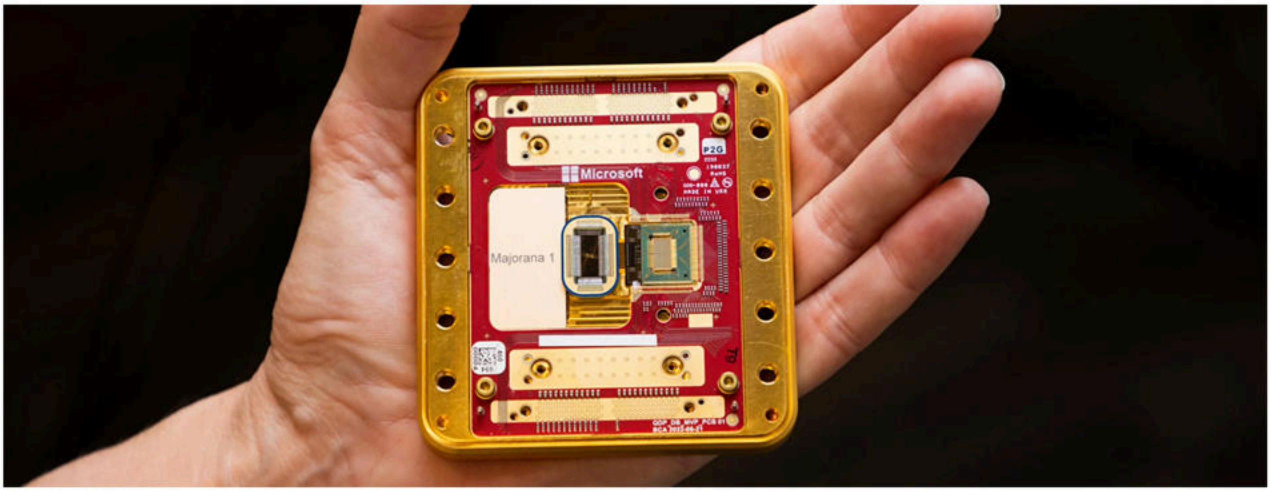
Silicon-spin qubits work by controlling the spin of single electrons inside tiny silicon structures, meaning quantum chips could one day be built much like today's classical processors. Topological qubits take an even more radical path, using exotic Majorana modes that naturally shield quantum information from noise, offering a future where stability is built into the physics itself rather than engineered around it.

Intel is pursuing a semiconductor-native pathway through silicon-spin qubits fabricated using the same 300 mm CMOS wafer processes used for conventional transistors. In 2023–2024, Intel introduced Tunnel Falls, a 12-qubit research chip fabricated on standard foundry equipment, demonstrating that quantum devices can, in principle, be mass-produced using mature silicon tools.

This strategy aims to leverage semiconductor process maturity to improve qubit uniformity, reproducibility, and long-term manufacturability, a key bottleneck in other architectures. Intel's research partners (including EPiQC, Sandia, and University of Rochester) have used Tunnel Falls for experiments in spin-state initialization, qubit transport, and multi-dot control, showing promising coherence and gate characteristics for early devices[55] . Intel's quantum roadmap is backed by corporate R&D funding exceeding $100+ million over several years, though Intel has not published precise totals. For now, silicon-spin systems are not yet cloud-accessible, but Tunnel Falls is available to select academic and government labs, positioning Intel's approach as a long-term manufacturability bet rather than a near-term commercial product.

Microsoft is pursuing one of the most ambitious directions in the sector: topological qubits based on Majorana zero modes. In February 2025, Microsoft announced the detection and control of topological Majorana modes, marking the first verified demonstration of non-Abelian statistics—an essential requirement for topological quantum computation[56].

[55] Intel (2025) Researchers progress with Tunnel Falls. Available at: https://www.intel.com/content/www/us/en/research/overview.html
[56] Microsoft (2025) Microsoft achieves important milestone toward topological qubits. Available at: https://techcommunity.microsoft.com/t5/azure-quantum-blog/microsoft-achieves-important-milestone-toward-topological-qubits/ba-p/4086892



Source: Microsoft's Majorana 1 Chip Carves New Path For Quantum Computing

In February 2025, the company unveiled Majorana 1, described as its first operational topological subsystem and a foundational block for a future large-scale machine designed to scale to a million qubits on a single chip. Microsoft positions this as a radically different path to fault tolerance, with potentially orders of magnitude lower error rates and significantly reduced stabilizer overhead compared to superconducting or trapped-ion systems. Microsoft's quantum program is backed by multi-billion-dollar internal investment, with Azure Quantum providing simulation, control systems, and a hybrid workflow stack. However, Microsoft's topological hardware is not publicly accessible, it is available only to internal researchers and select partners. Silicon-spin and topological qubits are still experimental, but they represent the architectures with the largest possible upside in long-term scaling. If successful, they offer pathways to manufacturable, dense, high-coherence qubit arrays, something neither superconducting nor trapped-ion systems have yet solved. Their breakthroughs would fundamentally rewrite the economic model of quantum hardware.

What distinguishes Microsoft's strategy is the scale of the end-state it is designed to reach. Rather than targeting incremental expansion into the thousands of physical qubits, Microsoft has articulated a long-term architectural objective on the order of one million qubits on a single chip, enabled by topological protection. This is not framed as a near-term roadmap milestone, but as a deliberate attempt to redefine the economics of quantum computing. If topological qubits deliver the intrinsic error resilience Microsoft is pursuing, the platform could bypass the conventional 1,000–10,000-physical-qubit scaling phase entirely. This makes Microsoft's approach one of the most asymmetric bets in the industry: exceptionally high risk, but with the potential to leapfrog existing fault-tolerant architectures if realized[57].

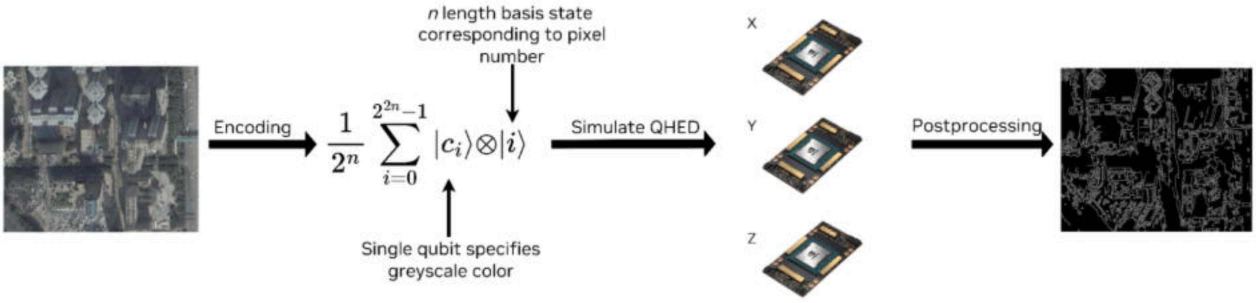
Hybrid Enablers - The Silent Force Multipliers

Some companies do not build quantum processors, they build the infrastructure that makes quantum usable, especially for hybrid workloads, orchestration, simulation, and cloud accessibility. As the field matures, these platforms are becoming just as strategically important as the hardware itself.

[57] The Quantum Insider (2025) Quantum Computing Roadmaps: A Look at The Maps And Predictions of Major Players. Available at: https://thequantuminsider.com/2025/05/16/quantum-computing-roadmaps-a-look-at-the-maps-and-predictions-of-major-quantum-players/

NVIDIA has become the backbone of hybrid quantum–classical computing. Its CUDA-Q platform (formerly CUDA Quantum), cuQuantum simulation libraries, and NVLink/NVQLink interconnects now serve as foundational technologies for accelerating quantum workflows[58]. By 2025, NVIDIA positioned itself as the orchestration layer for QPU–GPU integration, enabling real-time error mitigation, quantum circuit optimization, tensor-network simulation, and large-scale algorithm verification. These capabilities have already been used in research areas such as Quantum Chemistry requiring GPU-accelerated networks, Algorithm verification and Error-correction prototyping.

Because GPUs outperform CPUs on quantum-inspired algorithms by orders of magnitude, NVIDIA is effectively defining the standards for HPC–quantum interoperability. CUDA-Q, NVIDIA DGX hardware, and GPU-accelerated simulators are fully available to enterprises today through cloud platforms and on-prem systems. NVIDIA does not disclose quantum-specific spending, but its total R&D budget exceeds $12.91 billion (2025), and quantum infrastructure is a growing focus within that portfolio[59].



Source: NVIDIA CUDA-Q Powers Quantum Applications Research

Cloud platforms such as AWS Braket, Microsoft Azure Quantum, and Google Cloud's Quantum AI provide the standardized, developer-friendly access layer that allows enterprises to interact with multiple quantum hardware modalities without managing physical systems.

[58] NVIDIA (2025) Introducing NVIDIA CUDA-Q: The Platform for Hybrid Quantum-Classical Computing. Available at: https://developer.NVIDIA.com/blog/introducing-cuda-quantum-the-platform-for-hybrid-quantum-classical-computing

[59] NextPlatform (2025) NVIDIA Research: The Real Reason Big Green Commands Big Profits. Available at: https://www.nextplatform.com/2025/03/30/NVIDIA-research-the-real-reason-big-green-commands-big-profits/

AWS Braket offers access to superconducting, trapped-ion, and photonic processors, alongside managed hybrid workflows, tensor-network solvers, and analog Hamiltonian simulation. Amazon also offers the Quantum Embark program, an advisory-led engagement designed to support organizations at the earliest stages of their quantum adoption. The program provides structured guidance and domain expertise to help customers start from their most compute-intensive, business-critical problems, assess the current state of quantum capabilities, identify the most relevant technologies to prioritize, and make informed decisions about long-term resourcing and quantum strategy. Delivered by the Amazon Advanced Solutions Lab, Quantum Embark is organized into three modular components (Use Case Discovery, Technical Enablement, and Deep Dive) allowing participants to engage end-to-end or selectively, based on their existing maturity and objectives [60].

Azure Quantum integrates classical HPC with quantum hardware, resource estimation tools, and Microsoft's hybrid workflow stack. Google Quantum AI (via Google Cloud) supports development through TensorFlow Quantum, Cirq SDK, and limited-access Google processors via research partnerships.

These platforms are fully available today, offering enterprise SLAs, usage-based pricing, and unified environments for running quantum chemistry, optimization, ML experiments, and benchmarking. Majority of users access quantum hardware through cloud services, and a parallel shift is emerging toward on-premise or co-located quantum systems for enterprise and government environments. Companies such as IonQ are introducing rack-mounted quantum computers designed to sit beside classical HPC infrastructure in datacenters, allowing low-latency hybrid execution for workloads like simulation, optimization, and algorithm testing. Meanwhile, flagship systems with breakthrough performance, such as Quantinuum's H2 or IBM's Nighthawk, remain accessible primarily through commercial contracts, institutional partnerships, or dedicated research agreements.

The market is split between open-access cloud platforms that support experimentation, education, and hybrid algorithm development, and restricted-access, high-fidelity systems reserved for institutions pursuing scientific breakthroughs or competitive advantage. Hybrid enablers make this ecosystem functional by turning imperfect hardware into usable infrastructure, providing scalable GPU-backed compute, unified APIs, orchestration, diagnostics, simulation, and cross-hardware standardization that make quantum truly enterprise-ready.

[60] AWS Blogs (2024) AWS announces the Quantum Embark Program to help customers get ready for quantum computing. Available at: https://aws.amazon.com/blogs/quantum-computing/aws-announces-the-quantum-embark-program-to-help-customers-get-ready-for-quantum-computing/

2. Current Capabilities of Quantum Systems

2.1 Daily Use Cases Today

Daily use cases are already here, although they almost always sit inside hybrid quantum-classical workflows, not standalone quantum systems. In logistics, DHL and D-Wave (the world's first commercial supplier of quantum computers) ran a warehouse pilot where quantum-annealing was used to optimize the routes of automated guided vehicles (AGVs) in a high-congestion zone. This occurred over a two-week test at a major European fulfillment hub, and they reported a 13-15% reduction in total AGV transit time and a 22% drop in AGV idle time versus classical heuristics[61]. D-Wave also showcases a retail logistics case with 4,567 store locations, where its hybrid quantum solver generated 100 fully optimized delivery routes in under an hour, a task that would normally take human planners months to explore exhaustively[62]. These aren't toy problems. D-Wave says more than 60 commercial customers, including multiple Global 2000 firms, are already working with it on real-world quantum-hybrid applications across finance, manufacturing, and mobility, and more than 100 enterprise and institutional partners are in its broader ecosystem[63].

In finance, HSBC and IBM recently completed what they describe as the first quantum-enabled algorithmic trading trial for European corporate bonds, using IBM's Heron-class hardware in a hybrid pipeline; the model delivered up to a 34% improvement in predicting whether trades would execute at the quoted price compared with the best classical benchmark. This is a rare, quantified performance gain in a live market setting[64]. IBM is running similar work with Vanguard on portfolio-optimization studies, exploring how quantum routines can improve asset allocation under complex constraints[65]. On the industrial side, BMW's quantum computing challenge led to hybrid quantum-classical methods for sensor placement on vehicles with thousands of variables, showing that real automotive design problems can be mapped to near-term quantum hardware and simulators[66].

[61] Quantum Logistics (2021) DHL Supply Chain and D-Wave Trial Quantum Annealing for Warehouse Routing Efficiency. Available at: https://www.quantumlogistics.com/articles2021/15/04222021

[62] D-Wave (2024) Tackling route complexity: Quantum optimization for efficient, scalable logistics. Available at: https://www.dwavequantum.com/media/t5be11b4/logistics-routing-data-sheet.pdf

[63] D-Wave (2023) D-Wave announces new commercial customer engagements, cross-platform product enhancements at Qubits 2023. Available at: https://www.dwavequantum.com/company/newsroom/press-release/d-wave-announces-new-commercial-customer-engagements-cross-platform-product-enhancements-at-qubits-2023/

[64] IBM (2025) HSBC breaks new ground in quantum-enabled algorithmic trading with IBM quantum computers. Available at: https://www.ibm.com/quantum/blog/hsbc

[65] Business Insider (2025) AI startup SandboxAQ adds NVIDIA, Google as backers, raises additional $150 million. Available at: https://www.businessinsider.com/quantum-computing-financial-markets-portfolio-optimization-vanguard-ibm-hsbc-2025-10

[66] Pramanik, S. et al. (2022) Optimization of Sensor-Placement on Vehicles using Quantum-Classical Hybrid Methods. arXiv. Available at: https://arxiv.org/abs/2206.14546

All of this is happening on top of sizable infrastructure programs. IBM's Quantum Network now counts 250+ member organizations paying for access to its systems, including banks, utilities, and automotive OEMs[67] while D-Wave's customer base spans dozens of blue-chip enterprises[68]. At the ecosystem level, McKinsey estimates that quantum computing alone could represent $28 - 72 billion in annual market value by 2035, with total quantum-technology markets approaching $97 billion. A 2025 report cited by McKinsey & Company states that in 2024 "they poured nearly $2.0 billion into quantum-technology start-ups worldwide", which equates a 50% increase compared to 2023[69].

Quantum is also breaking new ground in material science and chemistry, where classical simulation reaches its limits. In May 2025, University of Sydney researchers performed the first dynamic chemical simulation on a trapped-ion quantum computer, modeling how molecules behave when excited by light, which was a milestone previously considered impossible for classical systems[70]. In November, MIT's Ernest Opoku introduced a method that removes guesswork from electron-interaction simulations, making quantum chemistry models faster and more accurate for sustainable-energy materials[71] . Researchers at the University of Michigan used quantum simulations to resolve a 40-year debate about the stability of exotic quasicrystals, another problem classical supercomputers struggled to handle[72] . Similar breakthroughs are emerging in drug discovery: IBM[73], Algorithmiq, and Cleveland Clinic[74] developed a hybrid workflow that calculates molecular energies more accurately than classical methods , and IonQ and Ansys demonstrated a medical-device simulation that outperformed classical HPC by 12%[75], one of the first documented cases of quantum surpassing classical computing in a real task.[76]

[67] University of Missouri (2024) Mizzou establishes IBM Quantum Innovation Center. Available at: https://engineering.missouri.edu/2024/mizzou-establishes-ibm-quantum-innovation-center/

[68] InvestorBrandNetwork (2025) D-Wave Quantum Inc. (NYSE: QBTS). Available at: https://www.investorbrandnetwork.com

[69] McKinsey (2025) The Year of Quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025

[70] University of Sydney (2025) Quantum simulation of chemical dynamics achieved for the first time. Available at: https://www.sydney.edu.au/news-opinion/news/2025/05/15/quantum-simulation-of-chemical-dynamics-achieved-for-the-first-t.html

[71] MIT (2025) Quantum modeling for breakthroughs in materials science and sustainable energy. Available at: https://news.mit.edu/2025/quantum-modeling-breakthroughs-materials-science-sustainable-energy-ernest-opoku-1119

[72] SpinQ (2025) Quantum Computing Industry Trends 2025: A Year of Breakthrough Milestones and Commercial Transition. Available at :https://www.spinquanta.com/news-detail/quantum-computing-industry-trends-2025-breakthrough-milestones-commercial-transition

[73] IntuitionLabs (2025) IBM Quantum's Role in Pharmaceutical Drug Discovery. Available at: https://intuitionlabs.ai/pdfs/ibm-quantum-s-role-in-pharmaceutical-drug-discovery.pdf

[74] The Quantum Insider (2025) Cleveland Clinic and IBM Use Hybrid Quantum Computing to Simulate Molecules. Available at: https://thequantuminsider.com/2025/11/19/cleveland-clinic-ibm-hybrid-quantum-molecule-simulation/

[75] Quantum Computing Report (2025) IonQ and Ansys demonstrate quantum speedup in engineering simulation workflow. Available at: https://quantumcomputingreport.com/ionq-and-ansys-demonstrate-quantum-speedup-in-engineering-simulation-workflow/

[76] The Quantum Insider (2025) IonQ's devices boost Ansys simulations, achieving up to 12% faster processing over classical computers. Available at: https://thequantuminsider.com/2025/03/20/ionqs-devices-boost-ansys-simulations-achieving-up-to-12-faster-processing-over-classical-computers/

Today, most real quantum computing activity happens through Quantum-as-a-Service (QaaS) platforms rather than on-premises hardware. Providers such as IBM Quantum Platform, Amazon Braket, Azure Quantum, and Google Quantum AI give users remote access to superconducting, trapped-ion, neutral-atom, photonic, and annealing processors, supported by high-fidelity simulators and removing the need for multimillion-dollar dilution refrigerators and cleanroom infrastructure. This delivery model has significantly lowered the barrier to entry for enterprises and research institutions, enabling global collaboration and rapid prototyping across chemistry, optimization, and materials-science problems[77].

Access costs vary by provider. IBM and AWS both offer free-tier simulators. Paid access to quantum hardware is billed on a usage basis. AWS Braket uses a per-task and per-shot model, with published rates starting at $0.30 per task plus a small fee per shot, as outlined in the AWS Braket Pricing documentation. IBM Quantum bills for hardware access by the compute-second through its Qiskit Runtime service, as described in the IBM Quantum Products and Services page[78]. Actual costs vary by backend, queue priority, and qubit quality.

Domain-specific QaaS is now emerging as well, with pre-built modules for drug discovery, financial optimization, and climate modeling, allowing organizations to obtain measurable insights before committing to full-scale quantum integration (N-iX; Medium). These platforms anchor the majority of quantum workloads today and form the practical foundation of enterprise experimentation in the NISQ era, without duplicating the outcomes and institutional progress covered in the following section.

Roughly 10,000 times more reliable operations are required for large-scale algorithms. This is why IBM's roadmap places its first fully fault-tolerant system, Starling, in 2029[79] , and why Google estimates more than 1000 physical qubits per logical qubit for modest error thresholds[80]. Expert consensus reflects this. 40% of professionals expect quantum advantage for narrow workloads within the next five years[81], while scalable enterprise deployments are expected to emerge in the early 2030s[82].

[77] SpinQ (2025) Quantum Computing as a Service: Use Cases and Benefits. Available at: https://www.spinquanta.com/news-detail/quantum-computing-as-a-service

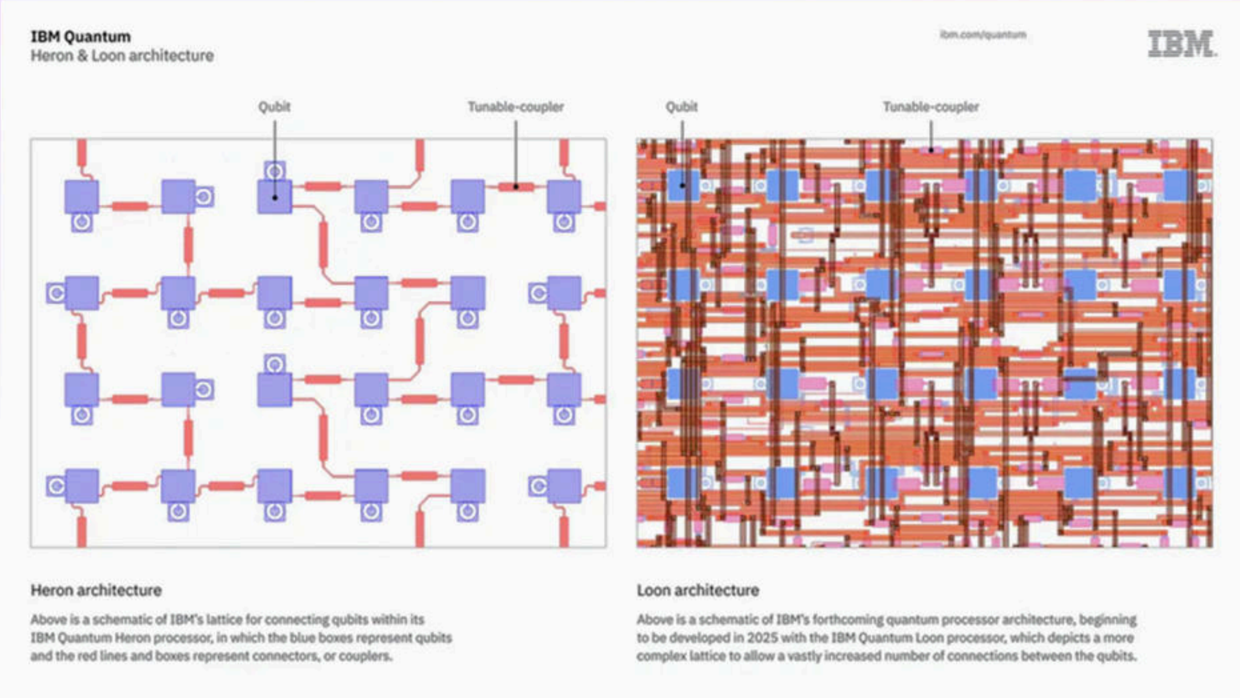
[78] IBM https://www.ibm.com/quantum/products

[79] Live Science (2025) 'The science is solve: IBM to build monster 10,000-qubit quantum computer by 2029 after solving science behind fault tolerance'. Available at: https://www.livescience.com/technology/computing/ibm-will-build-monster-10-000-qubit-quantum-computer-by-2029-after-solving-science-behind-fault-tolerance

[80] Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/

[81] Deloitte (2025) 'Quantum computing futures', Deloitte Insights, 11 August. Available at: https://www.deloitte.com/us/en/insights/topics/emerging-technologies/quantum-computing-futures.html

[82] McKinsey & Company (2025) The quantum revolution in pharma: Faster, smarter, and more precise. Available at: https://www.mckinsey.com/industries/life-sciences/our-insights/the-quantum-revolution-in-pharma-faster-smarter-and-more-precise



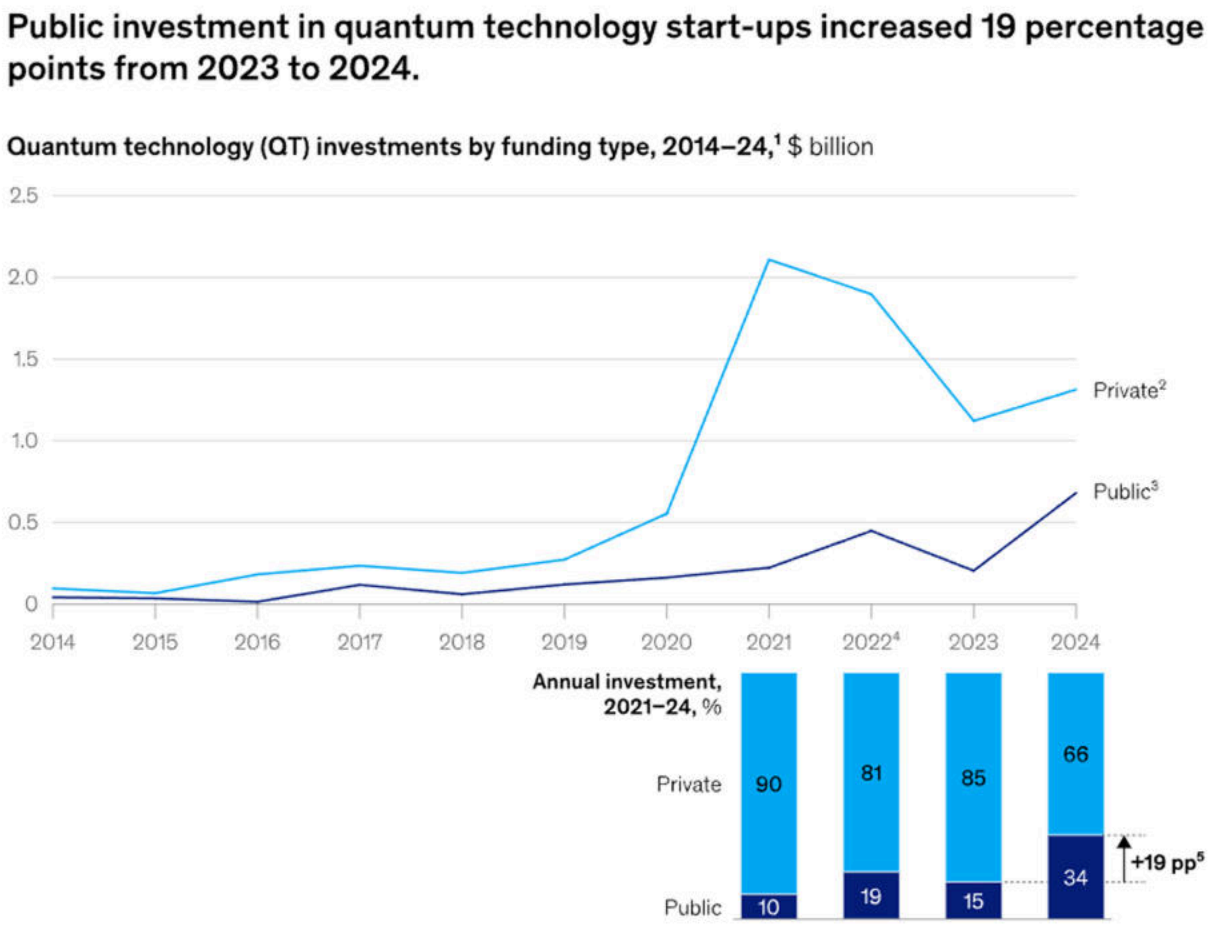
Source: IBM Will Build Monster 10,000-Qubit Quantum Computer By 2029 After 'solving Science' Behind Fault Tolerance — The Biggest Bottleneck To Scaling Up

The constraints are largely architectural and economic. Today, quantum systems deliver disproportionate value in high-impact scientific and optimization domains, rather than in the consumer workloads that dominate everyday applications. However, the trajectory is clear: with each generation, coherence improves, error rates decline, and the cost curve bends. The limitations of the current era are transitional, which positions the technology for materially broader utility over the coming decade.

Taken together, these examples illustrate how quantum computing is already creating measurable value within controlled, high-impact environments. Enterprises and institutions are able to deploy quantum capabilities today through hybrid workflows, cloud-based access, and targeted use cases where performance gains justify early adoption. This dynamic explains why the centre of momentum in quantum computing has shifted decisively toward institutional deployment, where experimentation can translate into strategic advantage well ahead of full fault tolerance.

2.2 Institutional progress

Institutions, not consumers, are driving quantum computing forward. Across the Fortune 500, more than 100 active pilots are underway, with roughly $300 million already invested in proofs of concept and a provider market expected to reach $1-2 billion by 2030. The prospective long-term economic value could reach $450-850 billion annually by 2040[83]. McKinsey's latest analysis shows a similar trajectory, projecting the market to grow from $4 billion in 2024 to $4 billion by 2035, driven by chemicals, life sciences, finance, and mobility[84]. Institutions expect the next five years to remain firmly in the NISQ era, with early quantum advantage emerging late in the decade and broader impact stretching into the 2030-2040 window.



Source: [The Year Of Quantum: From Concept To Reality In 2025]

Financial services remains one of the earliest and most organized adopters. A 2025 survey from the Bank of Finland found that four in five financial institutions believe quantum will be part of their business within ten years, though meaningful impact in the next five years will be less noticed[85].

[83] Boston Consulting Group (2024) Quantum Computing On Track to Create Up to US$850 Billion of Economic Value by 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040

[84] McKinsey & Company (2025) The year of quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025

[85] Bank of Finland (2025) Quantum computing is coming – Is the financial sector ready? Available at: https://www.bofbulletin.fi/en/2025/articles/quantum-computing-is-coming-is-the-financial-sector-ready/

JPMorgan is far ahead of the pack, responsible for two-thirds of all quantum job postings among the top 50 banks and over half of the sector's published quantum research. Their quantum-inspired portfolio work has delivered 1000 x speed-ups, and their collaboration with AWS and Caltech produced an 80% reduction in subproblem size for optimization pipelines compatible with NISQ algorithms[86]. Goldman Sachs is focused on derivatives pricing, exploring quantum signal processing and new encoding techniques for complex payoff structures[87].

Pharmaceutical and life-science companies are progressing in parallel, driven by chemistry's natural alignment with quantum mechanics. Leading adopters include Boehringer Ingelheim, Cleveland Clinic, Merck Group, and Roche, according to the Quantum Life Sciences Index[88]. IBM and Moderna are using quantum and generative AI to optimize mRNA sequence design, building on a 2024 demonstration where IBM's Heron processor was used for hybrid quantum–classical RNA structure prediction. A broader collaboration between IBM, Algorithmiq, RIKEN, and Cleveland Clinic introduced Subspace Quantum Diagonalization, enabling more accurate molecular-energy calculations than classical DFT methods and now being applied to drug-relevant molecules[89]. Additional partnerships include Google–Boehringer, Merck–QuPharma–BASF, and Roche–Quantinuum, spanning enzyme modeling, catalysis, and Alzheimer's research.

Manufacturing, mobility, and logistics are beginning to see operational gains. The World Economic Forum describes quantum as moving "from labs to factory floors" in 2025[90] . Early wins include Ford Otosan cutting scheduling time by 50%, TSMC using quantum diamond sensors for nanoscale defect detection, and the Port of Los Angeles reducing crane operations by 40% and truck wait times by two hours through hybrid quantum scheduling. Rotterdam is building a quantum-secure supply-chain backbone using QKD. Daimler and IBM are advancing Li-S battery chemistry via quantum simulation[91] , and Airbus has launched multi-country programs spanning aerodynamics, hydrogen fuel cells, and composite materials modeling[92]. BASF remains one of the most active industrial adopters through the QUTAC consortium, an industry-led consortium of major German/European companies and institutions, formed to drive the industrial adoption of quantum computing.[93]

[86] The Quantum Insider (2024) New Study from JPMorgan Chase and AWS Optimizes Large-Scale Portfolio Management with Quantum-Classical Hybrid Solutions. Available at: https://thequantuminsider.com/2024/09/19/new-study-from-jpmorgan-chase-and-aws-optimizes-large-scale-portfolio-management-with-quantum-classical-hybrid-solutions/

[87] FStech (2024) Goldman Sachs works with quantum scale-up to research options pricing algorithm. Available at: https://www.fstech.co.uk/fst/Goldman_Sachs_Works_With_Quantum_Scale_Up_To_Research_Options_Pricing_Algorithm.php

[88] The Quantum Insider (2025) New Quantum Index Monitors Progress in Life-Sciences Demand for Quantum Tools. Available at: htps://thequantuminsider.com/2025/05/08/new-quantum-index-monitors-progress-in-life-sciences-demand-for-quantum-tools/

[89] IntuitionLabs.ai (2025) IBM Quantum's Role in Pharmaceutical Drug Discovery. Available at: https://intuitionlabs.ai/pdfs/ibm-quantum-s-role-in-pharmaceutical-drug-discovery.pdf

[90] World Economic Forum (2025) Quantum Technologies: Key Opportunities for Advanced Manufacturing and Supply Chains. Available at: https://www.weforum.org/publications/quantum-technologies-key-opportunities-for-advanced-manufacturing-and-supply-chains/

[91] Airbus (2024) Quantum Leaps: Winners of Airbus and BMW Group's Quantum Computing Challenge Unveiled. Available at: https://www.airbus.com/en/newsroom/press-releases/2024-12-quantum-leaps-winners-of-airbus-and-bmw-groups-quantum-computing

[92] EQMagPro (2019) Mercedes enlists quantum computing to build a better electric vehicle battery. Available at: https://www.eqmagpro.com/mercedes-enlists-quantum-computing-to-build-a-better-electric-vehicle-battery/

[93] Munich Re (2021) Quantum Technology and Application Consortium (QUTAC): Munich Re participates in the establishment of the new consortium. Available at: https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/corporate-news/2021/2021-06-10-qutac.html

They are currently using quantum tools to accelerate catalyst development, which is critical given that catalysts impact more than 80% of BASF's production, and partnering with D-Wave, SEEQC, and NVIDIA to explore chemistry simulation and supply-chain optimization[94].

Energy and utilities represent another high value frontier. ExxonMobil, which is one of the earliest enterprise adopters joined the IBM Q Network in 2019 to explore optimization, climate modeling, and new materials for carbon capture[95]. BP and TotalEnergies follow closely, working on shipment routing, field-development optimization, and continuous-variable quantum methods for energy trading[96]. U.S. Department of Energy projects, often in collaboration with Rigetti, are investigating plasma dynamics for fusion, a workload beyond classical supercomputing[97].

Looking ahead, enterprise adoption will likely follow a two-phase arc. Between 2025 and 2027, most organizations will stay in structured experimentation. They will be focused on building teams, integrating QaaS platforms, and running targeted PoCs that are consistent with BCG's expectation of a $1-2 billion provider market by 2030[98]. From 2027 to 2030, the first narrow quantum advantages are expected in finance, chemistry, batteries, routing, and materials, supported by IBM's plan to deploy 200 logical qubits on Starling by 2029[99]. Regulators like the BIS, EU, and Finland are already encouraging institutions to plan for post-quantum cryptography and to build internal readiness. Across all sectors, quantum is becoming a strategic differentiator, but its impact will remain back-end. Consumers will benefit indirectly through better drugs, improved EV range, and more reliable supply chains and the computational shift will happen behind the scenes.

[94] D-Wave Quantum Inc. (2025) BASF and D-Wave announce completion of proof-of-concept project, demonstrating benchmark in manufacturing efficiency. Available at: https://www.dwavequantum.com/company/newsroom/press-release/basf-and-d-wave-announce-completion-of-proof-of-concept-project-demonstrating-benchmark-in-manufacturing-efficiency/

[95] Safety4Sea (2019) ExxonMobil, IBM to promote quantum computing for energy sector. Available at: https://safety4sea.com/exxonmobil-ibm-to-promote-quantum-computing-for-energy-sector/

[96] The Quantum Insider (2021) BP's partnership with the IBM Quantum Network out to reduce carbon emissions. Available at: https://thequantuminsider.com/2021/02/21/bps-partnership-with-the-ibm-quantum-network-out-to-reduce-carbon-%E2%80%8Eemissions/

[97] Department of Energy / Potomac Officers Club (2021) DOE awards fusion energy quantum computing project to Rigetti. Available at: https://www.potomacofficersclub.com/news/doe-awards-fusion-energy-quantum-computing-project-to-rigetti/

[98] Boston Consulting Group (2024) Quantum Computing On Track to Create Up to US$850 Billion of Economic Value by 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040

[99] IBM (2025) How IBM will build the world's first large-scale, fault-tolerant quantum computer. Available at: https://www.ibm.com/quantum/blog/large-scale-ftqc

2.3 Consumer stage

Consumers do not interact with quantum computers directly, but the technology is already influencing the systems they rely on every day. The clearest signal is emerging in AI, where hybrid quantum-classical models are beginning to deliver advantages that classical systems alone cannot. In May 2025, IonQ showed that adding a quantum circuit layer to an open-source LLM improved sentiment-classification accuracy, especially in rare-data scenarios. They also proved that performance increased with additional qubits, demonstrating an early form of quantum advantage inside real AI workloads. The same work projected meaningful energy savings in inference as models scale beyond 46 qubits, addressing one of the biggest bottlenecks in modern AI infrastructure[100]. These capabilities will reach enterprises first between 2025 and 2030, particularly in finance and materials science, before quietly shaping consumer experiences, including search, recommendations, personalization later on in the decade.

D-Wave Quantum Inc. has released a new research paper outlining a novel blockchain architecture that integrates quantum capabilities with traditional blockchain technology to enhance security and increase efficiency. In the paper, "Blockchain with Proof of Quantum Work,", D-Wave built and tested a "proof of quantum work" algorithm that uses quantum computation to generate and validate blockchain hashes. In this approach, quantum hashing is used to generate and validate blockchain transactions in a way that classical machines cannot efficiently replicate, and D-Wave successfully demonstrated a prototype deployment of this system across four of its cloud-accessible quantum processors in North America, marking one of the first distributed quantum computing applications[101] .

Quantum is also accelerating progress in materials and batteries, feeding directly into consumer products. Daimler and IBM simulations point to 20-30% improvements in lithium–sulfur batteries over today's lithium-ion cells[102]. BASF is using quantum tools to optimize catalysts involved in millions of tons of chemical production annually[103], and Airbus/BMW research is accelerating hydrogen fuel-cell and advanced-materials development. These breakthroughs won't show up as "quantum features," but as EVs with longer range, lighter materials, and safer, more efficient products by the end of the decade.

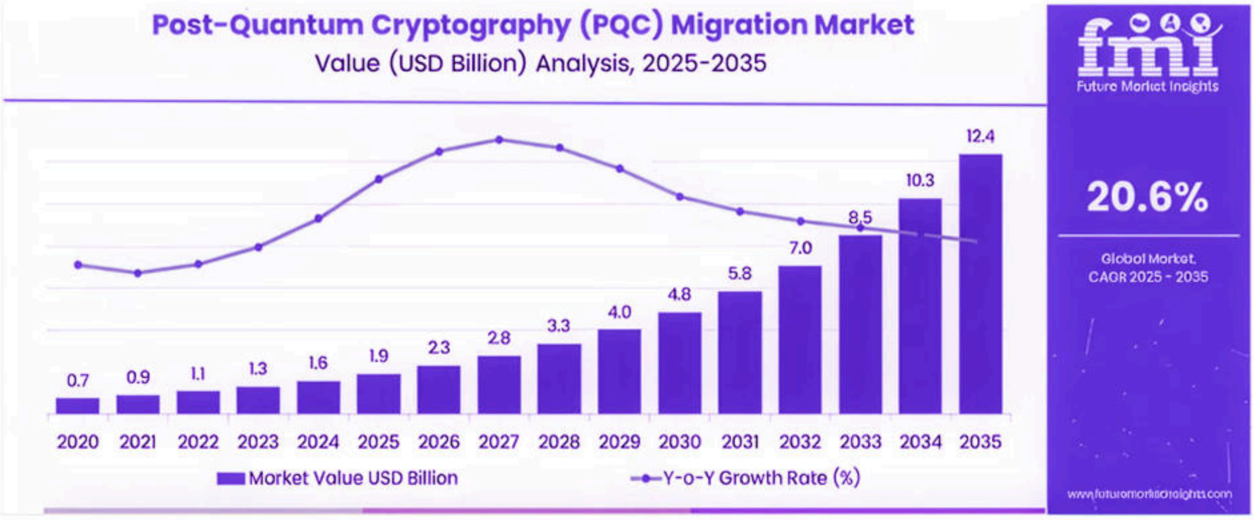
[100] IonQ (2025) IonQ Demonstrates Quantum-Enhanced Applications Advancing AI. Available at: https://ionq.com/news/ionq-demonstrates-quantum-enhanced-applications-advancing-ai

[101] D-Wave Quantum (2025) D-Wave Introduces Quantum Blockchain Architecture, Featuring Enhanced Security and Efficiency over Classical Computing. Available at: https://www.dwavequantum.com/company/newsroom/press-release/d-wave-introduces-quantum-blockchain-architecture-featuring-enhanced-security-and-efficiency-over-classical-computing/

[102] Eq-Mag Pro (2019) Mercedes enlists quantum computing to build a better electric vehicle battery. Available at: https://www.eqmagpro.com/mercedes-enlists-quantum-computing-to-build-a-better-electric-vehicle-battery/

[103] EE Times Europe (2024) BASF and Kipu Focus on End-User Mastery of Quantum Computing. Available at: https://www.eetimes.eu/basf-and-kipu-focus-on-end-user-mastery-of-quantum-computing/

Security is the second major area where consumers will feel quantum, quietly, but universally. Governments are mandating a global shift to post-quantum cryptography (PQC) which is a market projected to grow from $1.9 billion in 2025 to $12.4 billion by 2035[104]. The US has set a federal deadline of 2035, the UK targets 2028–2031, and the EU is coordinating national migration strategies[105]. Live deployments are already here. HSBC secured €30 million in FX transactions with quantum-safe methods, and 53% of banks are actively exploring PQC, with 25% already deploying it today from a communications perspective[106]. Quantum-secure networks are scaling too, with the QKD market expanding from $0.45 billion in 2025 to $4.49B by 2033[107]. Meanwhile, quantum-aided semiconductor R&D is beginning to influence the chips inside consumer devices. In late 2025, NYU researchers demonstrated superconductor-doped germanium wafers with 25 million Josephson junctions, enabling future hybrid classical–quantum chips with 5-10% lower power draw and 10–15% performance gains[108]. And quantum sensors, unseen but everywhere, are essentially already in premium EVs, smartphones, and wearables, with a market growing from $0.5 billion to $2.2 billion by 2045[109].



Source: Post-Quantum Cryptography (PQC) Migration Market

[104] FutureMarketInsights (2025) Post-Quantum Cryptography (PQC) Migration Market. Available at: https://www.futuremarketinsights.com/reports/post-quantum-cryptography-pqc-migration-market

[105] The Quantum Insider (2025) UK Sets Timeline, Road Map for Post-Quantum Cryptography Migration. Available at: https://thequantuminsider.com/2025/03/20/uk-sets-timeline-road-map-for-post-quantum-cryptography-migration/

[106] CoinLaw (2025) Quantum Cryptography in Finance Statistics 2025: How Quantum Cryptography is Transforming the Industry. Available at: https://coinlaw.io/quantum-cryptography-in-finance-statistics/

[107] SNS Insider (2025) Quantum Key Distribution Market Report. Available at: https://www.snsinsider.com/reports/quantum-key-distribution-market-8738

[108] LiveScience (2025) New semiconductor could allow classical and quantum computing on the same chip, thanks to superconductivity breakthrough. Available at: https://www.livescience.com/technology/computing/new-semiconductor-could-allow-classical-and-quantum-computing-on-the-same-chip-thanks-to-superconductivity-breakthrough

[109] Innovation News Network (2025) Quantum sensors will power $2.2bn tech revolution by 2045. Available at: https://www.innovationnewsnetwork.com/quantum-sensors-will-power-2-2bn-tech-revolution-by-2045/

3. How Quantum Hardware Evolved Over the Past Decade

3.1 Evolution Timeline (2015-2025)

Quantum computing's progress over the last ten years has not been linear but rather a series of decisive leaps. What initially began as fragile, millikelvin-cooled prototypes has now matured into a multi-modal ecosystem spanning superconducting qubits, trapped ions, and photonics. Between 2015 and 2025, the field shifted from "can this even work?" to "how fast can we reach fault tolerance?" Hardware stabilized, coherence improved by an order of magnitude, and for the first time, error correction crossed the threshold from theory to empirical proof. What follows is the decade that made today's momentum possible.

Pre - 2015 - Quiet Foundations

> Before quantum entered the public narrative, researchers were solving the fundamentals, which included cooling, stability, and control. A decisive moment came in 2014, when superconducting qubit fidelity passed 99%, proving reliable two-qubit operations were achievable and opening the door to scalable designs[110]. These were the early foundations that made the next decade possible.

2015 - 2020 - The First Real Machines

> This period marked the shift from theory to engineered systems. IBM's five-qubit device in 2016 demonstrated stable hardware accessible over the cloud, which was a symbolic moment that made quantum real for the broader world[111]. The major inflection came in 2019, when Google's Sycamore chip completed a computation in 200 seconds that would take classical machines millennia, offering the first practical evidence of quantum speed[112]. Meanwhile, trapped-ion systems achieved exceptionally high fidelities[113], and photonic platforms demonstrated scalable Gaussian boson sampling[114]. Quantum computing had moved from possible to promising.

2020–2023 - Scaling Up and Early Fault Tolerance

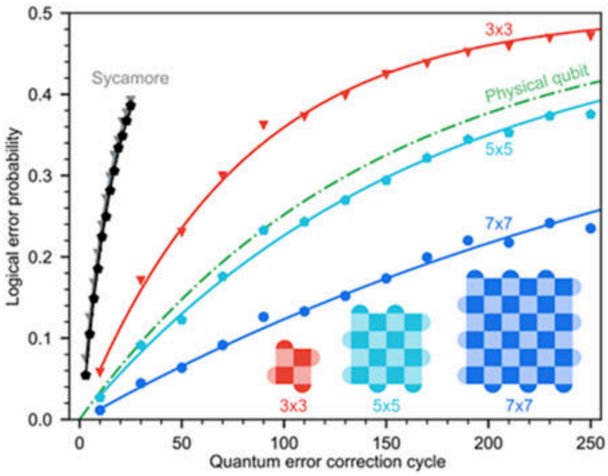
> By the early 2020s, the industry focused on scale and architecture. IBM crossed 100 qubits with the Eagle processor in 2021, enabled by breakthroughs in wiring and chip layout[115]. In 2023, IBM unveiled the 1,121-qubit Condor chip, marking the technical upper bound of the NISQ era[116]. moving from theory to engineering[117]. Photonic companies such as PsiQuantum[118] and Xanadu[119] advanced integrated architectures and programmable photonic systems. Fault tolerance was no longer abstract but becoming visible.

[110] Barends R, Kelly J, Megrant A et al. (2014) Superconducting quantum circuits at the surface code threshold for fault tolerance. Nature 508, 500–503. Available at: https://www.nature.com/articles/nature13717
[111] IBM (2021) Five years ago today, we put the first quantum computer on the cloud. Here's how we did it. Available at: https://www.ibm.com/quantum/blog/quantum-five-years
[112] Arute, F., Brandão, F. G. S. L., et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510. Available at: https://www.nature.com/articles/s41586-019-1666-5
[113] IonQ. Resources. Available at: https://ionq.com/resources
[114] Xanadu (2020) Xanadu brings photonic quantum computing to the cloud. Available at: https://www.xanadu.ai/press/xanadu-brings-photonic-quantum-computing-to-the-cloud
[115] IBM (2021) IBM Quantum breaks the 100-qubit processor barrier: 127-qubit "Eagle" quantum processor unveiled. Available at: https://www.ibm.com/quantum/blog/127-qubit-quantum-processor-eagle
[116] IBM (2023) IBM Unveils Quantum Roadmap Through 2033. Available at: https://www.ibm.com/quantum/blog/quantum-roadmap-2033

2023–2025 - The Fault-Tolerance Pivot

The most meaningful shift occurred here — from bigger to better. In 2024, Google's Willow processor demonstrated the first quantum error-corrected qubits that get exponentially better as they get bigger, showing that encoded error rates decline substantially with increasing surface-code size rather than accumulate, validating below-threshold error correction in a 105-qubit superconducting processor. Willow was engineered to optimize error suppression through both hardware and integrated machine-learning-assisted decoding and control, marking a strategic move toward systematic, scalable error correction. Supporting this advance, Google introduced a diagnostic technique achieving "verifiable quantum advantage" with the Quantum Echoes algorithm, solving complex physics problems (like revealing molecular structures) faster than supercomputers. This experiment measures "echoes" of information in an entangled system to understand quantum dynamics, paving the way for real-world applications in chemistry and materials science, with high accuracy on its 105-qubit processor.[120]

In 2025, this work matured into reproducible, system-level operation and became a cornerstone of Google's roadmap toward fault-tolerant quantum computing.[121] This confirms that large-scale fault tolerance is achievable.[122] IBM reinforced this pivot with Nighthawk (2025), optimized for deep, stable circuits rather than raw qubit count.[123] Trapped-ion systems reached commercial maturity, with IonQ releasing enterprise rack systems and acquiring technologies to boost entanglement speeds.[124]



Quantinuum continued delivering industry-leading logical qubits and fault-tolerant gates[125]. Photonic players pushed toward large-scale integration, advancing multi-chip architectures (PsiQuantum; Xanadu). By 2025, fault tolerance moved from concept to demonstrated capability, redefining the industry's focus toward practical scale-up.

[117] PostQuantum.com (2024). Microsoft Announces Record Breaking Logical Qubit Results. Available at: https://postquantum.com/industry-news/logical-qubit-microsoft/

[118] PsiQuantum (2025). PsiQuantum Raises $1 Billion to Build Million-Qubit Scale, Fault-Tolerant Quantum Computers. Available at: https://www.psiquantum.com/news-import/psiquantum-1b-fundraise

[119] Xanadu (2025). Xanadu Unveils First On-Chip Error-Resistant Photonic Qubit. Available at: https://www.xanadu.ai/press/xanadu-unveils-first-on-chip-error-resistant-photonic-qubit/

[120] Google (2024). Our Quantum Echoes algorithm is a big step toward real-world applications for quantum computing. Available at: https://blog.google/technology/research/quantum-echoes-willow-verifiable-quantum-advantage/

[121] Google Research (2024). Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/

[122] Google DeepMind (2024). AlphaQubit: Google's research on quantum error correction. Available at: https://blog.google/technology/google-deepmind/alphaqubit-quantum-error-correction/

[123] IBM (2025). IBM delivers new quantum processors, software, and algorithm breakthroughs on path to advantage and fault tolerance. Available at: https://newsroom.ibm.com/2025-11-12-ibm-delivers-new-quantum-processors-software-and-algorithm-breakthroughs-on-path-to-advantage-and-fault-tolerance

[124] IonQ (2024). IonQ Achieves Industry Breakthrough – First Trapped Ion Quantum System to Surpass 99.9% Fidelity on Barium. Available at: https://ionq.com/news/ionq-achieves-industry-breakthrough-first-trapped-ion-quantum-system-to-surpass-99-9-fidelity-on-barium

[125] Quantinuum (2023). Quantinuum's H1 quantum computer successfully executes a fully fault-tolerant algorithm with three logically-encoded qubits. Available at: https://www.quantinuum.com/press-releases/quantinuums-h1-quantum-computer-successfully-executes-a-fully-fault-tolerant-algorithm-with-three-logically-encoded-qubits

3.2 Next 3 Years (2025-2028)

The years 2025–2028 mark the industry's transition from NISQ experimentation to fault tolerance. The market is projected to grow more than 200% as investments, patents, and hardware performance accelerate in parallel. Global spending will likely increase from $1.8–3.5 billion in 2025[126] to $5.3–20.2 billion by 2028, reflecting a 33–42% CAGR and as much as a 5× expansion by 2030. Venture funding continues to grow, with $2 billion in 2024 and a strong 2025 run-rate of $1.67+ billion, alongside deep-pocketed industry commitments including JPMorgan's $2 billion quantum program and more than $10B in government allocations globally[127].

Patent activity mirrors the momentum. The past decade saw a 5× increase, with 5000+ quantum patent filings in 2024 and 13% annual growth in grants, led by IBM and Google[128]. This rapid IP expansion signals a shift from academic exploration to industrial competition. Technically, the next three years are defined by one theme: error suppression becomes real. Google's Willow platform (2024–2025) achieved exponential error reduction as qubits scale, the clearest validation to date of fault-tolerance principles[129]. Microsoft's progress on topological qubits suggests a path toward systems requiring 10–100× fewer physical qubits for each logical qubit, with room-temperature architectures projected to enter the hundreds of logical qubits by 2028[130]. IBM's roadmap accelerates in parallel. The Nighthawk and Heron families set the stage for Starling[131], a system targeting 200 logical qubits and 100M gate operations by 2028[132].

AI also becomes a defining accelerator. New neural-network-based methods demonstrated in 2025 can suppress noise without prior calibration, extending NISQ usefulness by 50–100% and enabling deeper circuits before full error-corrected machines arrive (McKinsey 2025). By 2028, major players converge around clearer roles. Google pushes the limits of error suppression; IBM targets the first production-grade fault-tolerant machine. Microsoft scales topological qubits, and IonQ advances high-fidelity trapped-ion systems with a roadmap toward 1,600 logical qubits by the decade's end[133]. The bottom line — 2025–2028 is the industry's bridge period, taking us from experimental prototypes to practical, production-grade quantum systems. Growth accelerates, error correction becomes credible, AI augments performance, and narrow quantum advantage begins to appear in chemistry and optimization workloads.

These developments marked a clear inflection point for the industry. With below-threshold error correction demonstrated and logical qubits operating reliably for the first time, the focus shifted decisively from proof of concept to scalable engineering. The question was no longer whether fault tolerance was achievable, but how quickly it could be extended, industrialized, and translated into a practical system, setting the stage for the next phase of growth between 2025 and 2028.

[126] MarketsandMarkets (2025). Quantum Computing Market Size, Share & Trends. Available at: https://www.marketsandmarkets.com/Market-Reports/quantum-computing-market-144888301.html
[127] McKinsey & Company (2025). The Year of Quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
[128] The Rapacke Law Group (2025). Top Quantum Computing Patents: Trends, Players, and Innovations in 2025. Available at: https://arapackelaw.com/patents/quantum-computing-patents/
[129] Google Quantum AI and Collaborators (2025). Quantum error correction below the surface code threshold. Available at: https://www.nature.com/articles/s41586-024-08449-4
[130] Microsoft (2025). Quantum Error Correction. Available at: https://quantum.microsoft.com/en-us/insights/education/concepts/quantum-error-correction
[131] SingularityHub (2023). IBM Is Planning to Build Its First Fault-Tolerant Quantum Computer by 2029. Available at: https:/ singularityhub.com/2023/12/06/ibm-is-planning-to-build-its-first-fault-tolerant-quantum-computer-by-2029/
[132] PostQuantum.com (2025). IBM Quantum Roadmap. Available at: https://postquantum.com/quantum-computing-companies/ibm/
[133] PostQuantum.com (2025). IonQ's 2025 Roadmap: Toward a Cryptographically Relevant Quantum Computer by 2028. Available at: https://postquantum.com/industry-news/ionq-roadmap-crqc/

4. Error Correction

As devices move from demos to real machines, the main story is no longer just qubit count, but how well we can beat errors using clever encoding. Quantum error correction (QEC) takes many imperfect physical qubits and bundles them into more reliable logical qubits, trading hardware overhead for dramatically lower error rates[134].

4.1 Why Error Correction Matters

Quantum computers are powerful but extremely fragile. Their qubits drift, lose information, or flip states within microseconds and they do this far more often than classical chips. Quantum Error Correction (QEC) is how the industry mitigates this. Instead of relying on a single unstable qubit, QEC bundles many qubits together so they act as one stronger "logical qubit," and continuously checks whether any part of the bundle has started to go wrong. When the physical qubits begin to misbehave, the system detects the issue and corrects it before the actual computation is affected. This is why leading players like Google, IBM, and Quantinuum use surface-code architectures. They allow the computer to automatically catch and fix mistakes fast enough to keep the calculation on track. It takes hundreds or even thousands of physical qubits to create one of these stable logical qubits, but this overhead is what turns today's noisy, short-lived devices into machines capable of running long, precise, economically meaningful quantum algorithms. Without error correction, a quantum computer can barely stay focused long enough to complete a useful task. With it, it becomes reliable enough to solve the complex problems it is built for.

4.2 Tangible Milestones - Error Correction Starts to Work

Over the last few years we've moved from theory to hard experimental evidence that QEC can actually improve things as systems scale. Google's team showed that a larger surface-code logical qubit (distance-5) had a lower logical error per cycle (≈2.9%) than a smaller code (distance-3, ≈3.0%), marking the first time increasing code size reduced errors rather than amplifying them[135]. Their 2024 "below-threshold" experiment with the Willow chip confirmed that properly engineered error correction can push systems into the regime where scaling the code truly pays off[136].

Microsoft used its error-correction stack on Quantinuum's trapped-ion hardware, from 30 physical qubits they distilled 4 reliable logical qubits, running over 14,000 experiments with no observed logical errors and claiming up to 800× better reliability than previous records[137].

[134] Raigada García, R. S. (2024) Quantum Error Correction Below the Surface Code Threshold. Available at: https://openaccess.uoc.edu/server/api/core/bitstreams/fef50b85-661c-430f-9a89-3711f8ce5fca/content

[135] Acharya, R. et al. (2022) Suppressing quantum errors by scaling a surface code logical qubit. arXiv:2207.06431. Available at: https://arxiv.org/abs/2207.06431

[136] The Verge (2024) Google reveals quantum computing chip with 'breakthrough' achievements. Available at: https://www.theverge.com/2024/12/9/24317382/google-willow-quantum-computing-chip-breakthrough

[137] Reuters (2024) Microsoft, Quantinuum claim breakthrough in quantum computing. Available at: https://www.reuters.com/technology/microsoft-quantinuum-claim-breakthrough-quantum-computing-2024-04-03/

Quantinuum has repeatedly demonstrated logical qubits that beat the best underlying physical qubits, including fault-tolerant entangling gates and, more recently, a fault-tolerant non-Clifford gate where the logical error rate is significantly lower than any unencoded gate on the same device[138].

IBM's latest roadmap centers on low-density parity-check (LDPC) codes and fast classical decoders, targeting a machine called Starling by 2029: ~200 logical qubits capable of running circuits with 100 million gates[139]. Using new LDPC-style codes (the "Gross code"), IBM estimates it can preserve 12 logical qubits with 288 physical qubits, roughly a 90% reduction in overhead compared to earlier surface-code estimates that needed almost 3,000 physical qubits for the same job[140].

4.3 Why This Matters and Where It's Heading

Error correction is the difference between today's NISQ devices and tomorrow's utility-scale, fault-tolerant quantum computers. Without it, noise limits useful circuits to a few hundred or thousand operations, with robust logical qubits, roadmaps from IBM, Google, Microsoft, and others aim for hundreds to thousands of logical qubits running algorithms with millions of steps without breaking down[141].

In practical terms, that's when quantum starts to matter for things like complex derivatives pricing, large-scale portfolio optimization, chemical simulation, and cryptanalysis, essentially workloads that demand long, deep circuits that go beyond today's capabilities. The progression in error correction over the last five years is therefore not just a technical curiosity but rather it is the main bottleneck and main lever for when quantum computing becomes economically and strategically relevant at scale.

As error correction moves from theoretical constraint to engineered capability, quantum computing begins to take its place within a broader computational system rather than standing apart from it. The next phase of progress is defined not by quantum hardware in isolation, but by how quantum processors integrate with classical infrastructure to form practical, hybrid architectures. To understand where quantum delivers value, and where it does not, it is therefore necessary to view it alongside the processors that already underpin modern computing.

[138] Quantinuum (2022) Logical qubits start outperforming physical qubits. Available at: https://www.quantinuum.com/press-releases/logical-qubits-start-outperforming-physical-qubits

[139] IBM Quantum (2024) IBM Quantum Development & Innovation Roadmap – 2024 Update. Available at: https://www.ibm.com/quantum/assets/IBM_Quantum_Developmen_&_Innovation_Roadmap_Explainer_2024-Update.pdf

[140] Quantum Computing Report (2025) IBM reveals more details about its quantum error correction roadmap. Available at: https://quantumcomputingreport.com/ibm-reveals-more-details-about-its-quantum-error-correction-roadmap/

[141] IBM Quantum (2024) IBM Quantum Development & Innovation Roadmap – 2024 Update. Available at: https://www.ibm.com/quantum/assets/IBM_Quantum_Developmen_&_Innovation_Roadmap_Explainer_2024-Update.pdf

5. Quantum Computers vs GPUs vs CPUs

5.1 The Three-Processor Universe

Modern computing is structured around three fundamentally different processor classes. CPUs handle general-purpose logic and orchestration. GPUs accelerate massively parallel classical workloads. QPUs use quantum-mechanical operations to target problems that scale exponentially on classical machines. These architectures serve different roles and form the foundation of a hybrid compute future.

To make this more concrete, a modern CPU may handle a few dozen hardware threads at once, whereas an NVIDIA H100 GPU delivers up to 70× higher AI throughput than the previous generation and reaches tens of trillions of operations per second, enabling simulation and AI workloads that would be impractical on CPUs alone[142].

Quantum processors take this even further. A 50-qubit QPU represents a quantum state containing 2^{50} amplitudes, over one quadrillion parameters, a space that cannot be brute-forced by any classical supercomputer today[143]. This "three-processor universe" determines how real enterprises will compute and is no longer abstract. CPUs coordinate workflows, GPUs accelerate heavy classical math, and QPUs provide access to quantum speedups in chemistry, cryptography, optimization, secure computation, and simulation. Together, they form the architecture of future digital infrastructure—where quantum becomes an extension of classical capability rather than a replacement[144]. To put the gap into perspective, no classical machine on Earth, even all data centers combined, can fully simulate a 60-qubit quantum state, a task that a QPU represents natively in one step. This limitation is repeatedly highlighted in quantum-complexity research, where classical simulation cost scales exponentially with qubit count.

5.2 Why CPUs, GPUs and QPUs are not a linear evolution

The progression from CPUs to GPUs to QPUs is often misunderstood as a simple upgrade path. In reality, each architecture was created for a different computational purpose and each one excels in a domain the others cannot handle[145]. CPUs remain the backbone of general-purpose computing. They prioritize sequential execution, low-latency control flow and flexible logic, making them ideal for operating systems, database engines, APIs and enterprise workflows. Their architectures are designed to manage memory, branching, and system-level orchestration with precision[146].

[142] NVIDIA DGX H100 — NVIDIA (2025) DGX H100. Available at: https://www.NVIDIA.com/en-us/data-center/dgx-h100/

[143] Arute, F. et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510. Available at: https://www.nature.com/articles/s41586-019-1666-5

[144] Arute, F. et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510. Available at: https://www.nature.com/articles/s41586-019-1666-5

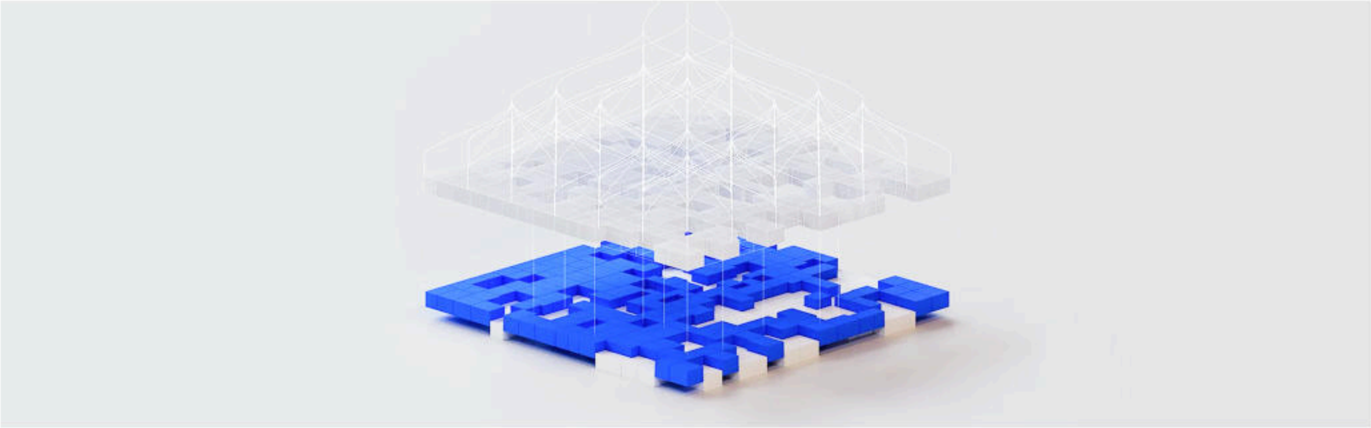
[145] ScienceDirect. Intel Architecture (IA). Available at: https://www.sciencedirect.com/topics/computer-science/intel-architecture

[146] AMD. AMD "Zen" Core Architecture. Available at: https://www.amd.com/en/technologies/zen

GPUs, by contrast, emerged to accelerate massively parallel mathematical workloads. They power the majority of AI and simulation tasks because they can process thousands of operations at once. As of 2025, nearly 90 percent of global AI training relies on GPU acceleration, and high-end systems such as the DGX H100 deliver performance levels reaching 1.5 petaflops[147]. Their strength lies in matrix operations, deep learning, physics simulation and real-time analytics that can be parallelized at scale[148].

QPU architectures represent a different paradigm entirely. Instead of manipulating bits, they operate on qubits through superposition and entanglement. This allows QPUs to target problem classes that grow exponentially on classical machines, such as complex optimization, cryptographic algorithms, quantum chemistry and certain forms of quantum machine learning. Today's systems remain in the NISQ era, but with 100+ qubit devices already available and fault-tolerant machines expected around 2028 to 2030, QPUs are beginning to fill computational gaps that classical systems cannot address[149].

The key insight is that these processors do not replace one another. They form a hybrid compute stack where CPUs orchestrate workflows, GPUs accelerate classical parallelism and QPUs solve quantum-native bottlenecks. The future of computing is not sequential. It is collaborative. [150] [151]



5.3 Real-world use cases

In practice, each processor class has a clear domain where it delivers the most meaningful real-world value. CPUs remain central to general computing. They manage operating systems, control logic, enterprise applications and transaction-heavy workloads such as SQL queries and distributed database operations. Their strength is reliability, flexibility and low-latency decision-making in systems that must remain both stable and adaptive[152].

[147] NVIDIA DGX H100 — NVIDIA (2025) DGX H100. Available at: https://www.NVIDIA.com/en-us/data-center/dgx-h100/
[148] NVIDIA. CUDA Zone. Available at: https://developer.NVIDIA.com/cuda
[149] Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/
[150] McKinsey & Company (2025) The Year of Quantum: From Concept to Reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
[151] World Economic Forum (2025) Quantum Technologies: Key Opportunities for Advanced Manufacturing and Supply Chains. Available at: https://www.weforum.org/publications/quantum-technologies-key-opportunities-for-advanced-manufacturing-and-supply-chains/
[152] ScienceDirect. Intel Architecture (IA). Available at: https://www.sciencedirect.com/topics/computer-science/intel-architecture

GPUs dominate AI and high-performance classical workloads. They enable neural network training, real-time inference, scientific modeling and advanced simulation across fields such as weather forecasting, molecular dynamics and fluid mechanics[153]. They also power modern graphics, rendering pipelines and large-scale data analytics infrastructure used in streaming, surveillance and cloud platforms[154]. QPUs address a different category of problems. In optimization, they are already being tested on logistics, supply chain routing and financial portfolio optimization, with pilots showing improvements ranging from 15 to 30 percent in route efficiency for DHL and a 40 percent gain in crane scheduling at the Port of Los Angeles. Financial institutions such as JPMorgan have demonstrated quantum-inspired methods delivering up to 1,000 times faster portfolio optimization compared to classical approaches.

In chemistry and materials science, QPUs are being used to simulate molecules, battery materials and catalysts that exceed classical scaling limits. Collaborations such as Mercedes-Benz with IBM, and Roche with Quantinuum, are early indicators of how quantum simulation may accelerate R&D cycles in drug discovery[155], battery design and materials engineering[156]. The security domain is also shifting. Global post-quantum cryptography migration is underway, with timelines stretching from 2028 to 2035 across major jurisdictions[157]. Quantum key distribution networks are already being deployed to protect supply chains and port infrastructure in parts of Europe[158]. Quantum machine learning is beginning to emerge as well. Demonstrations from IonQ show hybrid quantum-classical models outperforming classical baselines for certain feature mapping and sentiment analysis tasks, with measurable advantages appearing beyond the 46-qubit range[159].

The future of computing will not belong to one processor type but to an integrated landscape where classical and quantum systems reinforce each other. In that landscape, accelerated classical hardware plays a pivotal role, and no company illustrates this more clearly than NVIDIA.

5.4 Why NVIDIA Matters in a Hybrid Compute Future?

NVIDIA's position is reinforced by its dominance in the classical acceleration market, with its data-center segment alone generating over $35 billion in a single quarter (Q4 FY2025), underscoring the company's dominant position in classical acceleration. Given that industry forecasts expect the global data-center GPU market to expand from under $20 billion today to tens of billions by 2030, NVIDIA's infrastructure footprint remains unmatched among quantum-hardware players[160].

[153] NVIDIA. CUDA Zone. Available at: https://developer.NVIDIA.com/cuda
[154] NVIDIA DGX H100 — NVIDIA (2025) DGX H100. Available at: https://www.NVIDIA.com/en-us/data-center/dgx-h100/
[155] Boston Consulting Group (2024) Quantum Computing On Track to Create Up to US$850 Billion of Economic Value by 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040
[156] EQ Mag Pro (2019) Mercedes Enlists Quantum Computing to Build a Better Electric Vehicle Battery. Available at: https://www.eqmagpro.com/mercedes-enlists-quantum-computing-to-build-a-better-electric-vehicle-battery/
[157] FutureMarketInsights (2025) Post-Quantum Cryptography (PQC) Migration Market. Available at: https://www.futuremarketinsights.com/reports/post-quantum-cryptography-pqc-migration-market
[158] The Quantum Insider (2025) UK Sets Timeline, Road Map for Post-Quantum Cryptography Migration. Available at: https://thequantuminsider.com/2025/03/20/uk-sets-timeline-road-map-for-post-quantum-cryptography-migration/
[159] IonQ (2025) IonQ Demonstrates Quantum-Enhanced Applications Advancing AI. Available at: https://ionq.com/news/ionq-demonstrates-quantum-enhanced-applications-advancing-ai
[160] Investopedia(2025). How NVIDIA Makes Money. Available at: https://www.investopedia.com/how-NVIDIA-makes-money-4799532

As computing transitions from classical architectures into hybrid quantum-classical models, NVIDIA has positioned itself at one of the most critical junctions in the stack. Quantum computing still relies heavily on classical acceleration for simulation, data movement, training and post-processing. NVIDIA recognized this earlier than most. Instead of building a qubit technology of its own, it focused on becoming the orchestration and acceleration layer that every quantum workflow will depend on. This positioning mirrors NVIDIA's dominance in AI. Own the developer ecosystem, own the acceleration stack and remain hardware-agnostic[161].

CUDA-Q is central to this strategy. It allows developers to write quantum algorithms using a unified interface that runs seamlessly on real QPUs or GPU-based simulators. The platform supports every major qubit modality and integrates with widely used frameworks such as Qiskit, Cirq, Pennylane and CUDA Python[162]. By 2025, more than 10 000 developers were already using CUDA-Q, and industrial workflows such as BASF's chemistry simulations were running 60-qubit models directly on H100 GPUs[163].

5.5 CUDA-Q and GPU-Accelerated Quantum Simulation

NVIDIA's GPUs have become the leading platform for quantum circuit simulation, a capability that continues to be essential while hardware remains scarce and error-prone. GPU-based simulators now exceed 60 qubits, compared to the ~40-qubit ceiling typical of CPU clusters, and H100 GPUs can run quantum workloads up to one hundred times faster than CPU-based systems. This allows researchers to design, test and refine algorithms before consuming expensive QPU time. In practice, it democratizes quantum development and lowers the barrier to experimentation[164].

This simulation strength is what makes NVIDIA so important in hybrid computing. With CUDA-Q and cuQuantum, developers can run the heavy classical parts of quantum algorithms on GPUs and use QPUs only for the steps that truly require quantum mechanics. It creates a workflow where both systems play to their strengths[165]. Companies like BASF and research groups such as Fujitsu–RIKEN already use this model for catalyst design, materials development and complex simulations, because it lets classical and quantum compute operate together as a single, coordinated engine[166].

[161] McKinsey (2025) The Year of Quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
[162] NVIDIA. CUDA Zone. Available at: https://developer.NVIDIA.com/cuda
[163] Classiq (2025) Researchers Poised for Advances With NVIDIA CUDA-Q. Available at: https://www.classiq.io/insights/researchers-poised-for-advances-with-NVIDIA-cuda-quantum
[164] Classiq (2025) Researchers Poised for Advances With NVIDIA CUDA-Q. Available at: https://www.classiq.io/insights/researchers-poised-for-advances-with-NVIDIA-cuda-quantum
[165] NVIDIA (2022) Introducing NVIDIA CUDA-Q: The Platform for Hybrid Quantum-Classical Computing. Available at: https://developer.NVIDIA.com/blog/introducing-cuda-quantum-the-platform-for-hybrid-quantum-classical-computing/
[166] NVIDIA. High-Performance Computing. Available at: https://www.NVIDIA.com/en-gb/high-performance-computing/

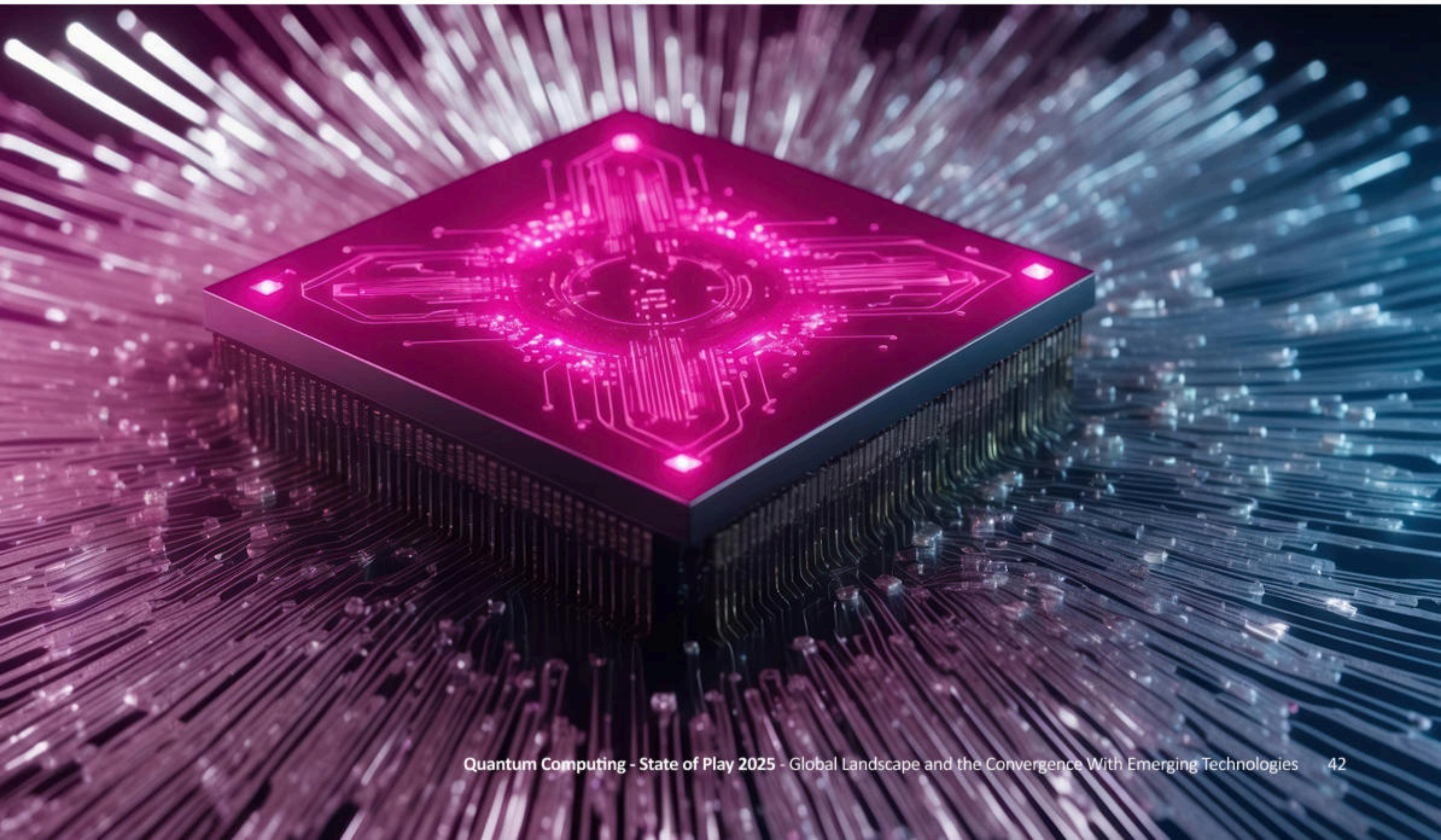
5.6 Strategic Positioning Across the Quantum Ecosystem

NVIDIA has chosen a hardware-agnostic strategy, integrating CUDA-Q with systems from major quantum players including IonQ, Rigetti, IBM and Quantinuum. This enables developers to build directly on NVIDIA's ecosystem regardless of which qubit platform ultimately dominates[167] . It is a direct parallel to the company's success in AI, where owning the software layer proved more valuable than building every model or chip[168].

This strategy positions NVIDIA to benefit from the quantum industry's growth regardless of hardware outcomes. Quantum systems will run in data centers. They will rely on GPU-accelerated simulation, GPU-accelerated post-processing and GPU-accelerated hybrid model training. With a projected seventy-billion-dollar quantum market by 2035, NVIDIA's value does not come from making qubits. It comes from owning the infrastructure and developer tools that sit at the center of the quantum-classical fusion[169].

While platform players like NVIDIA shape how quantum computing is built and accessed, the pace and direction of progress are also being set at a national and regional level. Quantum computing has become a strategic technology class, attracting long-term investment from governments alongside industry. Understanding the trajectory of the field therefore requires stepping beyond individual companies to examine how different countries are positioning themselves across research, talent, infrastructure, and supply chains.

[167] NVIDIA (2022) NVIDIA Announces Hybrid Quantum-Classical Computing Platform. Available at:
https://NVIDIAnews.NVIDIA.com/news/NVIDIA-announces-hybrid-quantum-classical-computing-platform
[168] IonQ (2024) IonQ to Advance Hybrid Quantum Computing with New Chemistry Application and NVIDIA CUDA-Q. Available at:
https://ionq.com/news/ionq-to-advance-hybrid-quantum-computing-with-new-chemistry-application-and
[169] McKinsey & Company (2025) The Year of Quantum: From Concept to Reality in 2025. Available at:
https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025



6. Country-by-Country Quantum Race

The global distribution of effort also matters. The United States, Europe, China, Japan, and a growing set of emerging hubs are all making long-term investments that create redundancy, talent mobility, and diversified supply chains. This geographic spread reinforces quantum's durability as a strategic technology class, meaning it is unlikely to stall, because too many nations and companies have meaningful stakes in its success.

6.1 United States - Federated, High-Intensity, Ecosystem-Led

The United States operates the world's most coordinated quantum ecosystem, combining federal research centers, commercial hardware leadership, and regulatory mandates that directly shape how quantum and post-quantum security will be deployed. Under the U.S. Department of Energy's quantum initiative framework, the U.S. has expanded long-term investment in quantum computing and quantum networking. In late 2025, the DOE renewed funding for its five National Quantum Information Science Research Centers, allocating $625 million[170], including $125 million each for SQMS (Superconducting Quantum Materials and Systems Center) at Fermilab and for Q-NEXT at Argonne National Laboratory[171]. This renews the U.S. commitment to a multi-center, multi-disciplinary national strategy rather than relying on single-lab breakthroughs.

The U.S. has taken a significant step toward building a national quantum internet. The Illinois Express Quantum Network (IEQNET) demonstrated synchronized quantum and classical signal transmission across deployed Chicago-area fiber connecting Argonne National Laboratory and Fermilab[172] , which is one of the most advanced metropolitan quantum networks globally[173]. To expand beyond testbeds, the DOE awarded $9 million over three years to the AQNET-SD (Advanced Quantum Networks for Scientific Discovery) initiative, supporting the early build-out of a nationwide quantum network backbone[174].

The commercial landscape reinforces the U.S. lead. IBM, Google, Microsoft, Amazon, and NVIDIA continue to run some of the world's most accessible high-qubit systems, cloud-based quantum services, and hybrid quantum-classical simulation environments, making the U.S. the default global testbed for early quantum algorithm development. Unlike many regions, the United States has already legislated the transition to post-quantum cryptography (PQC), directly linking regulatory security to expected progress in quantum hardware.

[170] U.S. Department of Energy (2025) Energy Department announces US$ 625 million to advance next phase of National Quantum Information Science Research Centers. Available at: https://www.energy.gov/articles/energy-department-announces-625-million-advance-next-phase-national-quantum-information
[171] Ames National Laboratory (2025) DOE renews SQMS Center with US$ 125 million to advance quantum technologies. Available at: https://www.ameslab.gov/news/doe-renews-sqms-center-with-125-million-to-advance-quantum-technologies
[172] Argonne National Laboratory / Fermilab (2022) Quantum network between two national labs achieves record synch. Available at: https://www.anl.gov/article/quantum-network-between-two-national-labs-achieves-record-synch
[173] Fermilab / IEQnet (n.d.) IEQnet: Fermilab's Quantum-Networking Project. Available at: https://ieqnet.fnal.gov/
[174] Fermilab (2023) Fermilab receives DOE funding to further develop nationwide quantum network. Available at: https://news.fnal.gov/2023/10/fermilab-receives-doe-funding-to-further-develop-nationwide-quantum-network/

In 2022, the Quantum Computing Cybersecurity Preparedness Act was signed into law, requiring all federal agencies to begin transitioning their systems to NIST-approved post-quantum algorithms in preparation for the quantum threat[175]. In 2024-2025, the U.S. Office of Management and Budget (OMB) issued PQC migration mandates requiring agencies to inventory vulnerable cryptography, begin active transition plans, and comply with NIST standards as they are finalized[176].

In November 2025, the National Security Strategy of the United States formally recognized quantum computing as a critical strategic technology in an intensifying global competition[177]. The document emphasized the U.S. objective of ensuring that American technologies and standards, particularly in artificial intelligence, biotechnology, and quantum computing, shape global norms and future innovation pathways. Quantum computing was positioned as both an economic and security imperative, closely linked to U.S. advantages in military and dual-use domains such as space, nuclear systems, autonomous platforms, and cyber operations. The Strategy made clear that sustained investment in research and development is necessary to preserve U.S. leadership as other states rapidly expand their own quantum capabilities.

Together these laws mean the U.S. is actively rebuilding its cybersecurity architecture in anticipation of large-scale quantum progress and not just developing quantum technologies in silos. The United States holds a full-stack quantum pipeline, including deep physics research, national-scale fabrication and networking programs, commercial clouds and hardware, and a regulatory environment that is already aligning to a post-quantum world. This combination puts the U.S. in the strongest position to operationalize quantum capability and protect national infrastructure as quantum technologies mature.

6.2 China - State-Orchestrated Scale and Quantum Communications Leadership

In 2016, China launched Micius, the world's first quantum-communication satellite (QUESS), enabling satellite-to-ground quantum key distribution (QKD) and unlocking a new paradigm for secure, long-distance quantum communications[178]. Using Micius, Chinese researchers successfully distributed entangled photon pairs and demonstrated quantum state teleportation between ground stations located 1,200 km apart, a record at the time[179].

[175] United States Congress (2022) Quantum Computing Cybersecurity Preparedness Act (H.R. 7535). Available at: https://www.congress.gov/bill/117th-congress/house-bill/7535

[176] Office of Management and Budget (2023) M-24-08: Strengthening Digital Accessibility and the Management of Section 508 of the Rehabilitation Act. Available at: https://www.whitehouse.gov/wp-content/uploads/2023/12/M-24-08-Strengthening-Digital-Accessibility-and-the-Management-of-Section-508-of-the-Rehabilitation-Act.pdf

[177] The White House (2025) National Security Strategy of the United States of America. Available at: https://www.whitehouse.gov/wp-content/uploads/2025/12/2025-National-Security-Strategy.pdf

[178] eoPortal (2025) QUESS. Available at: https://www.eoportal.org/satellite-missions/quess

[179] Yin, J. et al. (2017) Satellite-Based Entanglement Distribution Over 1200 Kilometers. Available at: https://arxiv.org/pdf/1707.01339

On the ground, China operates a 2,000-km fiber-optic quantum-secure communication backbone connecting Beijing and Shanghai (via Jinan, Hefei, etc.), activated in 2017 which is the first long-distance, intercity quantum-encrypted fiber link in the world[180]. The country has built what's described by its quantum research community as the "world's first integrated quantum communication network," combining more than 700 km of terrestrial optical fiber with satellite-to-ground links to achieve a total quantum link length of up to 4,600 km. This integrated network supports communications across multiple cities and applications[181].

According to independent analysis, China is among the top globally in public quantum funding, reportedly putting more than $15 billion into quantum communications, QIS, and related research. This gives it one of the most ambitious state-led quantum programs worldwide[182]. China's combined satellite and fiber-based programs place it among the global leaders in deployed quantum-secure communications infrastructure[183]. China's quantum strategy is not limited to labs or proofs of concept. Instead, it's building real, operational infrastructure that spans ground and space, with both public-sector backing and national-scale ambition.

Beyond large-scale infrastructure and applied programs, China continues to demonstrate strength in foundational quantum science, reinforcing its position at the leading edge of the field. Researchers at the University of Science and Technology of China recently realized a high-precision laboratory implementation of a thought experiment first proposed by Albert Einstein in 1927, testing whether a quantum particle's path and its wave-like interference pattern can be simultaneously observed. Using a single rubidium atom cooled near absolute zero as a movable detector, the experiment confirmed Niels Bohr's principle of complementarity, with results published in Physical Review Letters. While rooted in fundamental physics, the work advances experimental control at the quantum limit, with implications for quantum measurement, error control, and cryptographic security. Taken together with China's rapid progress in superconducting processors, quantum communications, and cloud-accessible systems, such advances underscore that China is no longer operating at the periphery of quantum innovation. The country has increasingly narrowed the gap with the United States across theory, experimentation, and systems engineering, supported by sustained state prioritization of quantum technology as a strategic domain. As leading researchers have noted, the global race toward quantum advantage has compressed to fine margins, and China now stands as a peer competitor shaping both the scientific foundations and the applied trajectory of next-generation quantum technologies[184].

[180] Chinese Academy of Sciences (2017) China's quantum satellite establishes photon entanglement over 1,200 km. Available at: https://english.cas.cn/newsroom/archive/news_archive/nu2017/201703/t20170324_175288.shtml
[181] University of Science and Technology of China (USTC) (2021) The world's first integrated quantum communication network. Available at: https://en.ustc.edu.cn/info/1007/3182.htm
[182] ITIF (2024) How Innovative Is China in Quantum? Available at: https://itif.org/publications/2024/09/09/how-innovative-is-china-in-quantum/
[183] Information Technology & Innovation Foundation (ITIF) (2024) How Innovative Is China in Quantum? Available at: https://itif.org/publications/2024/09/09/how-innovative-is-china-in-quantum/
[184] MSN (2025) China is no longer a follower in the race for quantum supremacy. Available at: https://www.msn.com/en-xl/news/other/china-is-no-longer-a-follower-in-the-race-for-quantum-supremacy/ar-AA1Sbg14

6.3 Europe (EU + UK) — Coordinated, Academic-Heavy, Consortium-Driven

Europe's core quantum commitment is the Quantum Technologies Flagship. This is a €1 billion, 10-year initiative launched by the European Commission to build a competitive and sovereign European quantum industry. The Flagship funds pan-EU projects across quantum computing, quantum communication, sensing, and enabling technologies, and connects thousands of researchers across the continent[185]. The Flagship's mission spans the full stack, including hardware and photonics to quantum algorithms and applications, and currently serves as the backbone of Europe's coordinated quantum R&D ecosystem[186]. At the national level, countries such as Germany, France, the Netherlands, Finland, and the UK run large-scale quantum programs focusing on photonics, quantum communication networks, neutral-atom platforms, materials science, and simulation, reflecting Europe's strengths in precision engineering and foundational physics[187]. Europe's quantum development is anchored by these specific national programs and infrastructure deployments that are reflecting a coordinated, long-term strategy.

Germany's €3 billion Quantum Technologies Program, part of its broader "Future Fund," includes major funding for hardware, cryogenics, and industrial-scale quantum computing initiatives[188]. France's €1.8 billion "France Quantum Plan", launched in 2021, supports a full-stack quantum strategy across superconducting qubits, neutral atoms, and photonics, with heavy investment into industrial players like Pasqal and Quandela[189]. The Netherlands operates Quantum Delta NL, a €615 million national initiative building a complete quantum supply chain, from qubit fabrication to Cryo-CMOS electronics. Then also hosting Europe's largest concentration of quantum startups and testbeds[190]. At the same time, Finland hosts Europe's first operational quantum computers via VTT and IQM, and has achieved successful national-scale quantum computing demonstrations[191]. Across the pond, the UK National Quantum Technologies Programme (NQTP) has committed £2.5 billion over 10 years to accelerate commercialization, including telecom-grade quantum networks and national testbeds such as BT's quantum-secured backbone[192].

Europe has begun aligning its regulatory posture with quantum's trajectory, especially in security, communications, and standardization.The EU Cybersecurity Act + NIS2 Directive requires enhanced cryptographic resilience for critical infrastructure, accelerating interest in post-quantum standards as part of long-term cybersecurity requirements[193]. European Telecommunications Standards Institute (ETSI) continues to lead global standardization in quantum key distribution (QKD) and quantum-safe cryptography, with dozens of norms under active development[194]. The European Quantum Communication Infrastructure (EuroQCI) aims to build a pan-EU quantum-secure network integrating fiber and satellites for government and critical services communications[195]. In parallel, The EU Space Programme is developing quantum-enabled secure satellites, positioning Europe for sovereign quantum communication capability across borders[196].

[185] European Commission (n.d.) EU Quantum Technologies Flagship. Available at: https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship
[186] Quantum Flagship. Quantum Flagship. Available at: https://qt.eu/
[187] CIFAR (2021) A Quantum Revolution: Report on Global Policies for Quantum Technology. Available at: https://cifar.ca/wp-content/uploads/2021/05/quantum-report-EN-11-accessible.pdf
[188] Federal Ministry of Education and Research (BMBF) (2022) Bekanntmachung: Quantencomputing-Förderung Deutschland. Available at: https://www.bmftr.bund.de/SharedDocs/Bekanntmachungen/DE/2021/05/3591_bekanntmachung.html
[189] EE Times Europe (2021) French President details €1.8 billion quantum plan. Available at: https://www.eetimes.eu/french-president-details-e1-8b-quantum-plan/
[190] Quantum Delta NL (n.d.) Quantum Delta NL Programme. Available at: https://quantumdelta.nl/programme-overview
[191] VTT Technical Research Centre of Finland (VTT) (2025) VTT and IQM launch first 50-qubit quantum computer developed in Europe. Available at: https://www.vttresearch.com/en/news-and-ideas/vtt-and-iqm-launch-first-50-qubit-quantum-computer-developed-europe
[192] UK Government (2023) New technologies on show at Quantum Showcase as Science Minister drives forward UK's £2.5 billion Quantum Strategy. Available at: https://www.gov.uk/government/news/new-technologies-on-show-at-quantum-showcase-as-science-minister-drives-forward-uks-25-billion-quantum-strategy
[193] European Commission (n.d.) EU Cybersecurity Act. Available at: https://digital-strategy.ec.europa.eu/en/policies/cybersecurity-act
[194] ETSI (2025) Industry Specification Group (ISG) on Quantum Key Distribution (QKD). Available at: https://www.etsi.org/committee/qkd
[195] European Commission (2025) European Quantum Communication Infrastructure (EuroQCI). Available at:https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci
[196] EU Agency for the Space Programme (2025) EU-Space Programme: Prepare Quantum Future. Available at: https://www.euspa.europa.eu/newsroom-events/news

Europe's strength lies in its coordinated, multi-country model: deep academic networks, cross-border standards, industrial consortia, and long-range national funding. Instead of relying on one corporate champion, Europe builds diverse, distributed quantum capabilities, increasing resilience and ensuring multiple routes to technological maturity.

6.4 Japan + South Korea — Hardware Depth and Roadmap-Driven Industrialization

Japan and South Korea are not just "followers" in the quantum race; they are building deeply engineered, industrial-grade ecosystems that sit on top of their semiconductor, telecom, and high-performance computing strengths. Japan anchors its quantum push in a series of government strategies. The Quantum Technology Innovation Strategy, the Vision of Quantum Future Society, and the Integrated Innovation Strategy 2025, all of which frame quantum as a pillar of "Society 5.0" and future industrial competitiveness[197]. Policy follow-through is backed by serious money. Recent analysis notes that the Japanese government has allocated ≈¥1.05 trillion (≈ $7.4 billion) to next-generation semiconductors and quantum computing R&D, explicitly naming institutions such as RIKEN, the University of Tokyo, Fujitsu, and Hitachi as core actors[198]. In parallel, a new supplemental budget proposes ≈¥400 billion (≈ $2.6 billion) for AI, quantum technologies, and fusion, reinforcing quantum as part of a broader "future compute" stack[199].

On the hardware side, Japan hit a major milestone in April 2025 when Fujitsu and RIKEN unveiled a 256-qubit superconducting quantum computer, described as a world-leading system and made accessible to companies and research institutions through the RIKEN–Fujitsu Collaboration Center[200]. A few months later, Japan launched its first fully homegrown quantum computer, developed without imported components at Osaka University's Center for Quantum Information and Quantum Biology (QIQB, operational July 2025). This was done using domestically designed superconducting chips and an open-source software toolchain[201]. Japan also leans into international industrial links. Joint funding calls such as the Japan–UK "Quantum Technologies for Innovation" program support bilateral projects with budgets up to ¥370 million on the Japanese side and £1.5 million on the UK side, directly tying Japanese labs into European commercialization pipelines[202].

Japan is deliberately pursuing sovereign quantum hardware and fabrication capability, backed by multi-billion-dollar budgets and exportable platforms. It is less noisy than the US or China, but strategically positioned as a high-quality hardware and component supplier in the global stack.

[197] RIKEN (2022) Quantum technology policy in Japan. Available at: https://quantum-innovation.riken.jp/archives/QI2022/program/pdf/PL-02-01.pdf
[198] Institute of Geoeconomics (2025) Japan needs to take the quantum-technology leap. Available at: https://quantum-innovation.riken.jp/archives/QI2022/program/pdf/PL-02-01.pdf
[199] QuantumComputer.blog (2025) Quantum AI Japan Government Unveil ¥400 B Budget for Fusion. Available at: https://quantumcomputer.blog/quantum-ai-japan-unveil-%C2%A5400-b-budget-fusion/
[200] Fujitsu (2025) Fujitsu Strengthens Global Quantum-Safe Cryptography Efforts. Available at: https://www.fujitsu.com/global/about/resources/news/press-releases/2025/0422-01.html
[201] LiveScience (2025) Japan launches its first homegrown quantum computer. Available at: https://www.livescience.com/technology/computing/japan-launches-its-first-homegrown-quantum-computer
[202] UK RI (2025) Japan-UK Joint Call for Quantum Technologies for Innovation. Available at: https://www.ukri.org/opportunity/japan-uk-joint-call-for-quantum-technologies-for-innovation/

South Korea treats quantum as an extension of its semiconductor and telecom strengths. Its National Quantum Strategy sets a clear 2035 horizon. A collaborative investment of over KRW 3 trillion (~$2.3 billion) by the government and private sector between 2023 and 2035 to build a "quantum economy." The roadmap targets concrete outcomes. Developing a 1000-qubit homegrown quantum computer, initiating intercity quantum networks, creating state-of-the-art quantum sensors, and training 2500 core quantum professionals plus 10 000 broader specialists by 2035[203].

South Korea also aims to capture around 10% of the global quantum technology market, supported by partnerships with IBM and IonQ to give local researchers and students hands-on access to quantum hardware[204]. More broadly, Korea has launched a $34 billion policy fund for strategic industries including semiconductors and AI, reinforcing the classical infrastructure and supply chains that quantum hardware will ultimately rely on[205]. South Korea is building a roadmap-driven quantum ecosystem that sits squarely on top of its semiconductor and telecom base. If it executes, Korea becomes a serious contender in mid-to-late-decade quantum hardware, networks, and integrated chip-level systems.

6.5 Southeast Asia — Singapore-Led, Region-Wide Network Building

Southeast Asia's quantum landscape is emerging but increasingly coordinated, with Singapore as the anchor and a web of ASEAN-level initiatives slowly forming around it. In May 2024, Singapore launched its National Quantum Strategy (NQS), backed by S$300 million under the Research, Innovation and Enterprise (RIE2025) plan to drive quantum as a national capability[206]. The NQS channels funding into four core initiatives: the Centre for Quantum Technologies (CQT), the Quantum Engineering Programme 3.0 (QEP 3.0), the National Quantum Processor Initiative (NQPI), and a National Quantum Scholarships Scheme (NQSS) for talent[207].

Under the NQS, CQT at the National University of Singapore is elevated to a flagship national R&D centre, coordinating quantum research talent and aligning academic programmes with engineering priorities in computation, communications, and sensing[208]. NQPI, led by CQT's director, is tasked with building domestic capabilities in quantum processor design and fabrication, and CQT now hosts multiple NQPI hardware projects[209].

[203] Ministry of Science and ICT (MSIT) (2023) In 2035, Korea Becoming the Global Hub for Quantum Economy! Available at: https://www.msit.go.kr/eng/bbs/view.do?bbsSeqNo=42&mId=4&mPid=2&nttSeqNo=828&sCode=eng&searchOpt=ALL
[204] The Quantum Insider (2023) South Korea to Invest $2.33 Billion in Quantum by 2035. Available at: https://thequantuminsider.com/2023/06/29/south-korea-to-invest-2-33-billion-in-quantum-by-2035/
[205] Reuters (2025) South Korea prepares $34 bln fund for national strategic industries. Available at: https://www.reuters.com/markets/asia/south-korea-prepares-34-bln-fund-national-strategic-industries-2025-03-05/
[206] RSIS (2025) Singapore's National Quantum Strategy Turns One. Available at: https://rsis.edu.sg/rsis-publication/idss/ip25069-singapores-national-quantum-strategy-turns-one/
[207] The Quantum Insider (2024) Singapore Invests S$300 Million in National Quantum Strategy. Available at: https://thequantuminsider.com/2024/05/30/singapore-invests-s300-million-in-national-quantum-strategy/
[208] National Quantum Office (2024) Close to S$300 million invested to drive Singapore's National Quantum Strategy over five years. Available at: https://nqo.sg/wp-content/uploads/2024/06/Media-Factsheet_NQO_National-Quantum-Strategy_27-May-clean-1.pdf
[209] Centre for Quantum Technologies (2025) CQT updates roles in national quantum programmes. Available at: https://www.cqt.sg/highlight/2025-06-national-quantum-programmes/

Institutionally, Singapore established the National Quantum Office (NQO) to oversee these programmes, connect public and private stakeholders, and act as a single coordination point for the NQS[210]. By 2025, NQO and CQT had also launched partnerships with global players such as Quantinuum via the National Quantum Computing Hub, reinforcing Singapore's role as a neutral APAC testbed for hardware, software, and talent development[211]. Beyond labs, Singapore is already deploying quantum-safe network infrastructure and positioning itself as Southeast Asia's first quantum-secure communications node[212].

The rest of ASEAN is earlier in the journey but still moving. Thailand has published a national quantum roadmap (2020–2029) and is hosting regional events like SEA Quantathon 2025 and the ASEAN Quantum Summit, helping shape an emerging SEA Quantum Network.Indonesia has established dedicated quantum research centres, while Vietnam launched VNQuantum, a national technology network that includes a quantum initiative to connect researchers, industry, and investors[213]. Malaysia has announced plans with partners to build a Quantum Intelligence Center and position itself as ASEAN's leading quantum hub by 2035, signaling its intent to compete for regional leadership[214].

From a policy lens, these efforts are increasingly framed in terms of quantum security and economic resilience: ASEAN commentary now explicitly discusses building quantum-safe networks, regional collaboration platforms, and talent pipelines to avoid falling behind the U.S.–China–EU triad[215]. Southeast Asia is evolving into a two-layer structure. Singapore as the research and infrastructure hub with dedicated national funding and institutions, surrounded by ASEAN neighbours building roadmaps, networks, and pilot programs. For global players, this creates a single high-trust beachhead (Singapore) plus a broader growth region for pilots and ecosystem building.

6.6 Middle East — Sovereign Quantum Bets in Saudi Arabia and the UAE

The Middle East is using quantum as part of a broader shift toward sovereign technology, energy optimization, and digital security, with Saudi Arabia and the UAE leading the charge. Saudi Arabia is explicitly tying quantum to Vision 2030 and a broader "quantum economy" narrative. A World Economic Forum and C4IR Saudi Arabia analysis describes how the Kingdom is crafting a National Quantum Agenda and "Quantum Economy Blueprint" to identify priority sectors, allocate funding, and design a national roadmap for investment, education, and R&D[216].

[210] National Quantum Office (2025) National Quantum Office. Available at: https://nqo.sg/
[211] Centre for Quantum Technologies (2025) Singapore's National Quantum Office and Quantinuum Forge Strategic Partnership to Accelerate Quantum Computing. Available at: https://www.cqt.sg/highlight/2025-11-nqo-quantinuum-strategic-partnership/
[212] RSIS (2025) Can ASEAN Secure a Quantum Future? Available at: https://rsis.edu.sg/rsis-publication/rsis/can-asean-secure-a-quantum-future/
[213] PostQuantum (2024) Quantum Technology Initiatives in Singapore and ASEAN. Available at: https://postquantum.com/quantum-computing/quantum-singapore-asean/
[214] The Quantum Insider (2025) MIMOS and SDT Collaborate to Establish Malaysia's First Quantum Computing R&D Center. Available at: https://thequantuminsider.com/2025/02/25/mimos-and-sdt-collaborate-to-establish-malaysias-first-quantum-computing-rd-center/
[215] Sagun Trajano, K. (2025) Can ASEAN Secure a Quantum Future? Available at: https://rsis.edu.sg/rsis-publication/rsis/can-asean-secure-a-quantum-future/
[216] World Economic Forum (2025) How Saudi Arabia is moving towards a quantum economy. Available at: https://www.weforum.org/stories/2025/01/how-saudi-arabia-is-moving-towards-a-quantum-economy/

Market and policy reports indicate that in 2024 the Kingdom launched a National Quantum Computing Strategy with an initial budget of around $200 million, aimed at building a quantum ecosystem spanning research centres, educational programmes, and industrial partnerships[217]. Quantum is now explicitly framed as a strategic enabler for energy, healthcare, finance, and national security under Vision 2030[218].

On the hardware side, Aramco and French startup Pasqal are deploying Saudi Arabia's first quantum computer, a 200-qubit neutral-atom system installed at Aramco's data centre in Dhahran. It is positioned as the Middle East's first quantum computer dedicated to industrial applications, targeting use cases in energy, materials, and complex optimization. Deployment was scheduled for the second half of 2025 and was reported in November 2025 as installed and operational[219]. In November 2025, the Saudi Quantum Network Alliance was launched by KACST to consolidate efforts in secure quantum communications and advanced technologies — a clear step toward dedicated quantum-secure infrastructure in the Kingdom[220]. Saudi Arabia is building a policy-first, infrastructure-second quantum strategy: a national agenda, dedicated funding, and an industrial-grade quantum computer focused on energy and strategic sectors. It wants to be a regional hub for quantum economy activity, not just a buyer of foreign systems.

The UAE's push is anchored in Abu Dhabi's Technology Innovation Institute (TII) and its Quantum Research Center and Cryptography Research Center. In 2021, TII announced plans to build the UAE's first quantum computer at its Quantum Research Center labs in Abu Dhabi, in collaboration with Qilimanjaro Quantum Tech. This marked a first for the region's hardware ambitions[221]. At the same time, TII's Cryptography Research Center released the UAE's first post-quantum cryptography software library, written in C and supporting multiple architectures, to help national institutions prepare for the quantum threat[222]. TII has since continued to develop quantum-safe libraries and open-source tools to estimate the security of PQC schemes and advise public and private entities on migration[223].

Alongside TII, MBZUAI (Mohamed bin Zayed University of Artificial Intelligence) is building advanced AI and compute capabilities, including research that touches quantum computing and cross-layer hardware–software optimization, giving the UAE a broader high-performance compute and AI corridor that quantum can plug into[224].

[217] Ken Research (2024) KSA Quantum Computing Market Outlook to 2030. Available at: https://www.kenresearch.com/industry-reports/ksa-quantum-computing-market
[218] Lucintel (2025) Quantum Computing Market in Saudi Arabia. Available at: https://www.lucintel.com/quantum-computing-market-in-saudi-arabia.aspx
[219] Reuters (2024) French startup Pasqal to deploy first quantum computer in Saudi Arabia. Available at: https://www.reuters.com/technology/french-startup-pasqal-deploy-first-quantum-computer-saudi-arabia-2024-05-20/
[220] Government of Saudi Arabia (2025) Aramco signs agreement to deploy first quantum computer in the Kingdom. Available at: https://my.gov.sa/en/news/1199329
[221] Technology Innovation Institute (TII) (2021) TII to Build UAE's First Quantum Computer. Available at: https://www.tii.ae/news/tii-build-uaes-first-quantum-computer
[222] EE Times Europe (2021) UAE to Get its First Quantum Computer and Cryptography Library. Available at: https://www.eetimes.eu/uae-to-get-its-first-quantum-computer-and-cryptography-library/
[223] ATRC (2023) Technology Innovation Institute Unveils World's First Open-Source Software Library for Cryptographic Hardness Estimation. Available at: https://www.atrc.gov.ae/news/technology-innovation-institute-unveils-worlds-first-open-source-software-library
[224] Mohamed bin Zayed University of Artificial Intelligence (MBZUAI) (2025) MBZUAI. Available at: https://mbzuai.ac.ae/

While the UAE has not yet published a standalone "national quantum law," its investment in quantum hardware plus PQC libraries signals a clear regulatory and strategic direction. Critical systems should be quantum-ready and quantum-resilient, with in-house capability to assess and deploy post-quantum schemes.

The UAE is building a crypto and security-centric quantum posture, with one foot in hardware via TII's quantum computer, and one foot in post-quantum cryptography and advisory services. For partners, it's an attractive testbed for quantum-safe protocols, critical-infrastructure security, and AI-plus-quantum research.

6.7 Switzerland - Stable, High-Investment Hub for Quantum Innovation

Switzerland punches far above its weight when it comes to quantum technology. Over the past two decades it has built a world-class quantum ecosystem, from its top universities (ETH Zurich, EPFL, University of Basel, University of Geneva) to public research institutes, spinning off private firms and startups, and now industry-oriented hubs[225].

A key node in this ecosystem is QuantumBasel, part of the uptownBasel innovation campus. QuantumBasel aims to make quantum computing and AI accessible to enterprises, academia and startups alike. As of end 2024, QuantumBasel, in partnership with IonQ, reportedly brought online what is claimed as Switzerland's first commercially usable quantum computer, a milestone signaling a shift from pure research to practical, application-oriented quantum services[226]. The investment volume of Uptown Basel, including Quantum Basel is over CHF 500 million[227].

Beyond single hubs, Switzerland has recently doubled down on nationwide coordination and funding for quantum research and innovation. The national Swiss Quantum Initiative (SQI), launched in 2022 by the federal government, pools together academia, research agencies and industry. SQI defines competitive calls, supports infrastructure development, fosters education, and promotes public-private collaboration in quantum technologies. Over 2025–2028 the initiative is backed by roughly CHF 82.1 million[228].

[225] Swissnex (2025) Switzerland: A Hub for Quantum – October 2025 update. Available at: https://swissnex.org/app/uploads/2025/10/Switzerland_Hub_Quantum_Oct2025_web.pdf
[226] Tageblatt (2024) Suiza inaugura su primera computadora cuántica comercial. Available at: https://tageblatt.com.ar/suiza-inaugura-su-primera-computadora-cuantica-comercial/
[227] MarketScreener (2023) IonQ and QuantumBasel Partner to Achieve Future Quantum Advantages With Deployment of Two Generations of IonQ Quantum Systems in Europe. Available at: https://www.marketscreener.com/quote/stock/IONQ-INC-117182090/news/IonQ-and-QuantumBasel-Partner-to-Achieve-Future-Quantum-Advantages-With-Deployment-of-Two-Generation-44169105/
[228] Swiss Federal Office for Education, Research and Innovation (SBFI) (2025) Swiss Quantum Initiative. Available at: https://www.sbfi.admin.ch/en/swiss-quantum-initiative-en

This combination of deep academic expertise, active private-sector engagement, infrastructure build-out, and stable public support gives Switzerland a remarkably balanced quantum ecosystem, one that spans hardware and software research, quantum communications, sensing, cryptography, and commercialization. For a small, neutral nation, this breadth makes Switzerland a credible global hub for quantum innovation and a model for how public and private actors can co-craft a quantum-ready future.

6.8 Why Global Investment Matters

Taken together, the national strategies across North America, Europe, Asia and the Middle East reveal a clear global pattern. Quantum is now treated as strategic infrastructure, not an experimental research field. Countries are funding quantum hardware, building communication networks, establishing post-quantum security requirements, and training dedicated technical workforces. These investments span universities, national laboratories, industrial partners and sovereign funds, creating a level of global redundancy that makes quantum progress structurally resilient.

This worldwide distribution of effort also means that quantum no longer depends on breakthroughs in a single region. The United States is advancing networks and regulation. China is scaling satellite and fiber-based quantum communications. Europe is coordinating consortia and standards. Japan and South Korea are strengthening hardware and fabrication. The Middle East and Southeast Asia are building sovereign capability and national testbeds. With so many regions moving in parallel, the trajectory of quantum technologies has become global, coordinated and increasingly inevitable.

As quantum technologies move from isolated research programs to globally distributed infrastructure, attention naturally shifts from whether they will arrive to how they will be deployed securely and at scale. A technology class advancing across borders, institutions, and networks raises foundational questions about trust, coordination, and resilience in digital systems. This brings the focus to the underlying infrastructure layers that must evolve alongside quantum computing, most notably, how data, assets, and transactions are secured in a post-quantum world.

7. Does Quantum Need Blockchain?

The question people usually ask is whether quantum will break blockchains. A more useful starting point is the reverse. Modern blockchains already depend on high-performance computing, and they are on a trajectory where both GPUs and, eventually, QPUs become part of the infrastructure. The paradox is that the same quantum capabilities that could accelerate blockchain also threaten to undermine the cryptography that keeps it secure.

7.1 Blockchains already rely on GPU-class acceleration

Even after the industry's shift from proof-of-work to proof-of-stake, the most advanced parts of the blockchain stack are quietly becoming GPU-native. It is no longer only about mining. Zero-knowledge rollups, privacy-preserving protocols and validity proofs have turned proof generation into a heavy HPC workload. Research on zk-SNARKs and FRI-based proof systems shows that the heaviest parts of generating a proof are exactly the kinds of computations GPUs are good at. Tasks like multi-scalar multiplication, building polynomial commitments and constructing Merkle trees can all be parallelized. When these steps are moved from CPUs to CUDA-enabled GPUs, prover time drops significantly and memory usage becomes far more efficient. It's a result confirmed across multiple studies[229].

This is already visible in real-world blockchain systems. zkSync's proving stack, for example, has required high-memory GPUs to generate proofs efficiently, with early production setups using GPUs with around 40 GB of VRAM to keep proving times low (as documented in Matter Labs' engineering notes and public Boojum upgrade materials)[230]. The Boojum prover and other leading zero-knowledge ecosystems now explicitly optimize their pipelines to be GPU-friendly, because faster proof generation directly translates into higher network throughput and lower transaction costs for users[231].

Beyond Ethereum rollups, entire blockchain ecosystems are already reorganizing themselves around GPU-heavy proving. Networks like Aleo have actively encouraged former GPU miners to redeploy their hardware toward generating zero-knowledge proofs, effectively turning GPUs into the new economic engine of the network. At the same time, leading hardware teams are developing hybrid ASIC–GPU architectures designed specifically to accelerate proving at scale, signalling an industry-wide recognition that high-performance compute is becoming foundational to next-generation blockchain infrastructure[232].

[229] Ni, N. & Zhu, Y. (2023) Enabling zero knowledge proof by accelerating zk-SNARK kernels on GPU. Journal of Parallel and Distributed Computing, 173, 20–31. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0743731522002246
[230] Matter Labs (2023) Introducing the ZK Stack: Your framework for building modular, sovereign, ZK Chains. Available at: https://blog.matter-labs.io/introducing-the-zk-stack-c24240c2532a
[231] The Block (2023) zkSync launches new proof system called Boojum for Era mainnet. Available at: https://www.theblock.co/post/239880/zksync-launches-new-proof-system-called-boojum-for-era-mainnet
[232] CoinGeek (2025) Modular ASIC-GPU Hybrids: ZK Proofs in Bitcoin mining. Available at: https://coingeek.com/modular-asic-gpu-hybrids-zk-proofs-in-bitcoin-mining/

For any blockchain builder, the implication is straightforward. If your roadmap includes ZK rollups, privacy rails or proof-intensive compliance and identity systems, you are already operating in a GPU-dependent world. The protocol may be decentralized, but its ability to scale is tied directly to access to high-performance compute. In practice, the future of throughput, cost efficiency and user experience is increasingly restrained by the availability of serious acceleration infrastructure, and not by consensus design.

7.2 Will blockchains need QPUs in the future?

Looking ahead, it is reasonable to expect that some blockchain workloads will eventually tap into QPUs as specialized accelerators, even if the core consensus remains classical.

There are at least three plausible avenues.

Proof generation and cryptography

Research on quantum computing and blockchain points to a future where quantum systems are used not only to attack cryptosystems but also to accelerate new, quantum-resilient ones. Frameworks that combine distributed ledgers with post-quantum cryptography and advanced auditing already appear in the literature, particularly for high-value data such as multimedia and regulated workloads[233]. As quantum hardware matures, some of the heaviest algebra in proof systems or signature schemes could migrate to QPUs for specific subroutines, especially where there is a clear theoretical speedup.

On-chain optimization problems

Blockchains already embed complex optimization in MEV, routing, auction design, liquidations and cross-chain rebalancing. Quantum optimization has shown promise for logistics, finance and scheduling problems that look structurally similar to some of these tasks[234]. In a future hybrid stack, one can imagine validators or specialized "quantum oracles" calling QPUs to solve certain optimization steps more efficiently, then committing results back to the chain.

Quantum-aware consensus and sharding.

Early research is emerging on consensus protocols and sharded architectures that assume a quantum-capable environment, either to improve scalability or to design post-quantum consensus from first principles[235]. While this is still highly experimental, it illustrates a direction where QPUs work as a design tool for new forms of distributed agreement.

[233] Khan, A. A., Laghari, A., Almansour, H., Jamel, L., Hajjej, F., Estrela, V. V., Mohamed, M. A. & Ullah, S. (2025) Quantum computing empowering blockchain technology with post-quantum resistant cryptography for multimedia data privacy preservation in cloud-enabled public auditing platforms. Journal of Cloud Computing: Advances, Systems and Applications, 14(1), 1-16. Available at: https://link.springer.com/article/10.1186/s13677-025-00771-8
[234] AIP (2024) Survey on the Potential Impact of Quantum Computing. Available at: https://pubs.aip.org/aip/acp/article/3263/1/030006/3359154
[235] INSPIRE-HEP (2025) Practical Iterative Quantum Consensus Protocol With Sharding Construction. Available at: https://inspirehep.net/literature/3064105

None of this changes the fact that blockchains will continue relying on classical hardware for the near and foreseeable future. What is emerging however is a more capable hybrid model. CPUs and GPUs will remain the backbone for validation, node operations and proof generation, while QPUs start to appear as specialized co-processors for the most complex computational tasks. It's a future where quantum becomes an additional layer of strength for blockchain systems.

7.3 The paradox: quantum as both accelerator and existential threat

A more strategic and burning question to address is not whether blockchains will integrate quantum, but whether they will survive quantum in their current form. Most major blockchains rely on public-key cryptography based on elliptic curves and finite-field arithmetic. A sufficiently powerful, fault-tolerant quantum computer running Shor's algorithm could break these schemes, allowing an attacker to derive private keys from public addresses, forge signatures or impersonate validators[236]. Grover's algorithm also offers a quadratic speedup against symmetric primitives and hash functions, which means security margins for things like proof-of-work or address generation can be eroded if parameters are not adjusted.

Recent surveys describe this as a direct challenge to the "foundational components" of blockchain security[237]. The risk is not only future attacks. There is a harvest-now-decrypt-later problem. Adversaries can already record encrypted traffic or on-chain ciphertexts today and decrypt them once cryptographically relevant quantum computers (CRQCs) arrive[238]. For systems that need multi-decade confidentiality or value preservation, this is a serious concern.

Regulators and standards bodies have started to move..

In the United States, the **Quantum Computing Cybersecurity Preparedness Act** requires federal agencies to plan the migration of their IT systems to quantum-resistant cryptography, and OMB memo M-23-02 instructs them to inventory cryptographic systems and prepare PQC transition plans. NIST published the first official post-quantum cryptography standards in August 2024, including lattice-based key encapsulation (Kyber) and digital signatures (Dilithium, SLHDSA+), formally establishing the algorithms that will replace RSA and ECC in federal systems. According to NIST, any cryptography that is not quantum-resistant will be considered obsolete by 2035, the target year by which U.S. federal systems must complete their transition to post-quantum standards[239] . In Europe, the Commission has issued a Recommendation and a coordinated roadmap encouraging Member States to transition critical infrastructure to quantum-resistant encryption by around 2030, backed by ENISA guidance under NIS2 [240].

[236] Yang, Z., Alfauri, H., Farkiani, B., Jain, R., Di Pietro, R. & Erbad, A. (2024) A Survey and Comparison of Post-quantum and Quantum Blockchains. IEEE Communications Surveys & Tutorials, 26(2), 967–1002. Available at: https://arxiv.org/pdf/2409.01358
[237] Reddy, N. R. et al. (2025) QuantumShield-BC: Quantum secured blockchain framework for enhancing post-quantum data security. Scientific Reports. Available at: https://www.nature.com/articles/s41598-025-16315-8
[238] Reuters (2025) Europol body: Banks should prepare for quantum computer risk now. Available at: https://www.reuters.com/technology/cybersecurity/europol-body-banks-should-prepare-quantum-computer-risk-now-2025-02-07/
[239] U.S. Congress (2022) Quantum Computing Cybersecurity Preparedness Act (H.R. 7535). Available at: https://www.congress.gov/bill/117th-congress/house-bill/7535
[240] European Commission (2024) Commission publishes Recommendation on Post-Quantum Cryptography. Available at: https://digital-strategy.ec.europa.eu/en/news/commission-publishes-recommendation-post-quantum-cryptography

The UK's National Cyber Security Centre has warned that organizations should plan to complete migration to post-quantum cryptography by 2035, with concrete milestones starting in 2028[241]. A Europol-led Quantum Safe Financial Forum has urged banks and financial institutions to assess quantum risk now, highlighting that customer data and authentication records being stored today may be decrypted in the future[242].

Industry is reacting in parallel. Cloudflare, for example, has begun rolling out PQC across its network and zero-trust stack, and surveys show that more than half of large organizations are actively assessing quantum risk and preparing PQC roadmaps, even if many are behind schedule[243].The Quantum Stablecoin Settlement Network (QSSN) unveiled by BTQ is a next-generation settlement framework designed to help banks, payment providers, and digital asset platforms issue and manage stablecoins with built-in protections against quantum-era cybersecurity threats. QSSN is intended to support a range of stablecoin models including institutional deposit tokens and widely used fiat-backed coins while preserving existing token standards, user workflows, wallets, and compliance processes. The framework is positioned to address evolving regulatory timelines that call for quantum-safe financial infrastructure by upgrading only the core functions used for privileged transactions such as minting, burning, and administrative controls with quantum-resistant cryptography[244].

This approach aims to enable compliance with emerging federal mandates for quantum resilience without disrupting market interaction or operational infrastructure. QSSN further aligns with broader stablecoin market growth and regulatory initiatives by proposing technical standards to ensure stablecoins are quantum-secure by design as part of critical financial systems. For blockchain ecosystems, this creates a paradox. On one hand, they stand to benefit from quantum-accelerated optimization, simulation and possibly new forms of consensus. On the other, their current cryptographic foundations are explicitly named in policy documents and technical reports as targets that must be replaced. To put it simply, quantum is both the most powerful accelerator blockchains have ever seen and the clearest reason they must evolve. The chains that win the next decade are likely to be the ones that treat quantum not as a distant research topic but as a design constraint and a co-design partner, moving early on post-quantum cryptography while exploring where quantum acceleration can unlock entirely new categories of on-chain applications.

This paradox, quantum as both accelerator and existential threat, implies a transition point rather than a dead end. As regulatory timelines crystallize and technical pathways toward post-quantum security become clearer, the focus shifts from risk identification to strategic response. The relevant question is no longer whether systems such as blockchains must adapt, but how this adaptation reshapes the architecture of digital infrastructure more broadly. Understanding where the quantum trajectory leads next requires stepping back from individual technologies to examine the structural changes now set in motion.

This analysis is not an endorsement of any specific blockchain design, but a structural assessment of post-quantum requirements.

[241] The Guardian (2025) UK cybersecurity agency warns over risk of quantum hackers. Available at: https://www.theguardian.com/technology/2025/mar/20/uk-cybersecurity-agency-quantum-hackers
[242] Reuters (2025) Europol body: Banks should prepare for quantum computer risk now. Available at: https://www.reuters.com/technology/cybersecurity/europol-body-banks-should-prepare-quantum-computer-risk-now-2025-02-07
[243] Barron's (2025) Cloudflare is bulking up to fight the quantum attack. Available at: https://www.barrons.com/articles/cloudflare-quantum-computers-cybersecurity-7e41dbaa
[244] PR Newswire (2025) BTQ Technologies Unveils Quantum Stablecoin Settlement Network (QSSN) Available at: https://www.prnewswire.com/news-releases/btq-technologies-unveils-quantum-stablecoin-settlement-network-qssn-302489583.html

8. Where the Quantum Trajectory Leads Next

With the technical foundations improving and the strategic implications now widely recognized, the global response has entered a new phase. Capital investment, government budgets, patent activity, and corporate roadmaps all point to accelerating momentum across the ecosystem. The data that follows shows how quickly quantum is moving toward commercial scale and why the world's largest economies and enterprises are treating it as a priority technology.

8.1 Key Stats, Market Growth & Patent Activity

The global quantum industry is accelerating from experimental systems to early commercial adoption. Quantum hardware and software markets are projected to reach $1–2 billion by 2030, with potential $450–850 billion annual economic value by 2040, according to BCG[245]. McKinsey estimates $4 billion in quantum revenue in 2024 rising to $72 billion by 2035, with the strongest early impact in chemicals, life sciences, mobility, and finance. Venture capital activity surged, with $1.25 billion invested in Q1 2025, double the previous year, and roughly 70% of funding now directed toward hardware approaching commercial readiness[246].

Since 2020, the industry has produced 5,000+ quantum patents, led by IBM, Google, IonQ, Rigetti, and major Chinese institutions. Patents focus on error correction, qubit fabrication, quantum algorithms, and hardware control software[247]. Research output on fault-tolerant quantum computing has doubled between 2023 and 2025, signalling a rapid shift toward scalable designs[248].

8.2 Funding, Government Budgets & Deep-Tech Breakthroughs

Government investment remains the dominant catalyst. The US has committed $10+ billion over five years via DOE, NSF, DARPA, and NIST, including $1.2 billion for fault-tolerant quantum computing research. China remains the largest investor globally with ~$193 billion in cumulative quantum funding since 2021 across 250+ projects. The EU continues the €1 billion Quantum Flagship with €100 million yearly through EuroHPC. South Korea, Singapore, India, Saudi Arabia, and UAE all maintain multi-year national quantum programs[249].

[245] Boston Consulting Group (2024) Quantum Computing On Track to Create Up to $850 Billion of Economic Value By 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040
[246] McKinsey (2025) The Year of Quantum: From Concept to Reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
[247] The Quantum Insider (2025) Top Quantum Computing Companies. Available at: https://thequantuminsider.com/2025/09/23/top-quantum-computing-companies/
[248] SpinQ (2025) Quantum Computing Industry Trends 2025: A Year of Breakthrough Milestones and Commercial Transition. Available at: https://www.spinquanta.com/news-detail/quantum-computing-industry-trends-2025-breakthrough-milestones-commercial-transition
[249] SpinQ (2025) Quantum Computing Industry Trends 2025: A Year of Breakthrough Milestones and Commercial Transition. Available at: https://www.spinquanta.com/news-detail/quantum-computing-industry-trends-2025-breakthrough-milestones-commercial-transition

Global research labs continue to hit major performance milestones. Google's Willow chip demonstrated below-threshold behavior and exponential error suppression[250]. IBM's roadmap (Heron → Flamingo → Starling) scales from 133 physical qubits to 200+ logical qubits and targets billion-operation fault-tolerant circuits by 2029[251]. IonQ's Forte system achieved 36 algorithmic qubits and is fully integrated with AWS and NVIDIA CUDA-Q[252] . In photonics, Xanadu demonstrated the first on-chip error-resistant photonic qubit (2025). Neutral-atom innovators like QuEra continue deploying scalable lattice systems[253].

IBM plans to deliver Starling, a fault-tolerant-ready system with 200 logical qubits, by 2029[254]. Google is advancing logical-qubit performance through the Willow program. Microsoft is building a Majorana-based architecture with AI-enhanced decoders[255]. NVIDIA is unifying quantum and GPU workflows through CUDA-Q[256]. Cloud platforms AWS Braket, Google Quantum AI, and Azure Quantum dominate early QaaS adoption.

8.3 Government & Military Adoption and Rising Cybersecurity Urgency

Quantum technologies are being integrated into defense and national-security systems. The US Department of Defense is deploying quantum-enhanced secure communication, sensing, and radar capabilities. China has operational quantum communication satellites and secure military links. NATO now classifies quantum readiness as a strategic priority. Multiple governments have introduced quantum-safe cryptography requirements in defense procurement[257].

The shift to post-quantum cryptography is accelerating. NIST standardized the first PQC algorithms in August 2024, and the US government has mandated full federal migration by 2035, with the UK and EU accelerating timelines. Financial institutions, defense contractors, cloud providers, and blockchain ecosystems are adopting PQC to counter "harvest now, decrypt later" threats[258].

[250] Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/
[251] IBM Quantum (2025) How IBM will build the world's first large-scale, fault-tolerant quantum computer. Available at: https://www.ibm.com/quantum/blog/large-scale-ftqc
[252] NVIDIA (2025) "Quantum Computing." Available at: https://www.NVIDIA.com/en-gb/high-performance-computing/
[253] Xanadu (2025) Xanadu unveils first on-chip error-resistant photonic qubit. Available at: https://www.xanadu.ai/press/xanadu-unveils-first-on-chip-error-resistant-photonic-qubit/
[254] IBM (2025) IBM Quantum hardware and roadmap — Hardware for useful quantum computing. Available at: https://www.ibm.com/quantum/hardware
[255] Microsoft (2025) Quantum Error Correction. Available at: https://quantum.microsoft.com//en-us/insights/education/concepts/quantum-error-correction
[256] NVIDIA (2025) CUDA Quantum. Available at: https://developer.NVIDIA.com/cuda-quantum
[257] Hirvonen, A., Savolainen, J. & Snellman, H. (2025) Quantum computing is coming – Is the financial sector ready? Bank of Finland Bulletin. Available at: https://www.bofbulletin.fi/en/2025/articles/quantum-computing-is-coming-is-the-financial-sector-ready/
[258] PQShield (2025) The BIS publishes quantum-readiness roadmap for the financial system. Available at: https://pqshield.com/the-bis-publishes-quantum-readiness-roadmap-for-the-financial-system/ ,
FutureMarketInsights (2025) Post-Quantum Cryptography (PQC) Migration Market. Available at: https://www.futuremarketinsights.com/reports/post-quantum-cryptography-pqc-migration-market

Conclusion

Quantum computing is no longer a distant research topic confined to laboratories and academic journals. It is becoming a strategic input into how institutions think about computation, security, and long-term technological advantage. The groundwork for the impact of fault-tolerant systems is being laid now through hybrid infrastructure, institutional experimentation, and cryptographic transition.

As countries scale national strategies and industry roadmaps sharpen, the shift from possibility to expectation becomes clear. The world is preparing for quantum capability to sit alongside classical compute and advanced AI as part of the same strategic stack. We see the same pattern everywhere. Rising government budgets, accelerating private capital, deepening research output, and the first hints of fault-tolerant design. These trends reinforce the same trajectory introduced at the start of the paper. The years ahead mark a fundamental shift in how organizations will approach computation and security.

The convergence of quantum, AI, and high-performance compute is more than a technological milestone. It is a strategic realignment. Institutions that recognize this and begin preparing early will shape the next era of advantage. Those that delay will find themselves adapting to systems they did not influence. The progression documented across these sections shows how quickly this landscape is solidifying and how the decisions made now will set direction for the next decade.For decision-makers, the implication is clear. Quantum readiness is not about deploying large-scale machines today. It is about ensuring that organizations can integrate quantum capabilities as they become viable, while protecting systems that cannot be easily replaced or retrofitted. This includes building hybrid quantum–classical workflows, aligning security architectures with post-quantum standards, and developing the internal expertise required to evaluate rapidly evolving claims and capabilities.

The evidence reviewed throughout this report indicates that the effective decision horizon has now compressed to the next 24–36 months, during which institutions must move from passive monitoring to structured engagement. This phase is characterized by hybrid quantum–classical experimentation via cloud platforms, early domain-specific pilots, and formal assessment of post-quantum cryptographic exposure for long-lived data and critical systems. Decisions taken during this interval shape long-term architectural flexibility, security posture, and cost trajectories in ways that are not easily reversible.

Consistent with the trajectory described in earlier sections, the period from 2027 to 2030 is expected to mark the emergence of narrow, production-grade quantum advantage in specific institutional domains, including chemistry, finance, optimization, and scientific simulation. This is happening alongside the transition of post-quantum cryptography from strategic initiative to mandatory compliance requirement. Beyond 2030, as fault-tolerant systems progress from pilot environments toward production use, quantum capability is likely to shift from a differentiating asset to a baseline component of advanced compute infrastructure. Institutions that have not established internal expertise, vendor relationships, and migration pathways by this stage face materially higher costs across talent acquisition, capital investment, and accelerated remediation timelines.

For Tier-1 stakeholders, the quantum transition is therefore not a distant point but an active structural shift driven by three converging forces: a mandated post-quantum security upgrade cycle (2025–2030), documented institutional productivity gains from early hybrid deployment (2025–2028), and sustained geopolitical investment exceeding $20 billion annually, which underwrites long-term execution. Organizations that establish credible quantum readiness by 2027 benefit from accumulated learning, earlier amortization of capital, and privileged access to constrained talent and infrastructure. Those that delay face compounding penalties across talent acquisition, capital expenditure, compliance remediation, and competitive positioning. The implications are durable rather than cyclical, positioning quantum computing as a defining technology transition of the 2025–2035 decade, with permanent consequences for security posture and institutional advantage.

Quantum advantage will not arrive everywhere at once, and it will not transform consumer experiences overnight but exposure to quantum risk will be widespread, and preparedness will be uneven. Institutions that act early will have time, options, and strategic flexibility. The organizations that build literacy, readiness, and strategic positioning today will lead the markets of tomorrow. The opportunity is not only to prepare for the future but to help define it.

Appendix

1. Post-Quantum (2025) IBM Quantum Computing. Available at: https://postquantum.com/quantum-computing-companies/ibm/
2. IBM (2025) IBM Quantum Roadmap 2025. Available at: https://www.ibm.com/roadmaps/quantum/2025/
3. IBM (2025) 300 mm Fab for Quantum Chips. Available at: https://www.ibm.com/quantum/blog/300mm-fab
4. IBM. Quantum-centric Supercomputing. Available at: https://www.ibm.com/think/topics/quantum-centric-supercomputing
5. IoT World Today (2025) IBM Reports $1B in Cumulative Quantum Computing Revenue. Available at: https://www.iotworldtoday.com/quantum/ibm-reports-1b-in-cumulative-quantum-computing-revenue
6. AbuGhanem, M. (2025) IBM quantum computers: evolution, performance, and future directions. The Journal of Supercomputing, 81, article 687. Available at: https://link.springer.com/article/10.1007/s11227-025-07047-7
7. IBM (2025) Hybrid quantum-classical simulation of periodic materials. Available at: https://research.ibm.com/publications/hybrid-quantum-classical-simulation-of-periodic-materials
8. IBM (2025) IBM Quantum Cloud. Available at: https://quantum.cloud.ibm.com/
9. IBM (2025) Quantum computing. Available at: https://www.ibm.com/think/topics/quantum-computing
10. Google Quantum AI (2024) Our quantum error correction milestone. Available at: https://quantumai.google/qecmilestone
11. Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/
12. Google DeepMind / Google Quantum AI (2024) AlphaQubit tackles one of quantum computing's biggest challenges. Available at: https://blog.google/technology/google-deepmind/alphaqubit-quantum-error-correction/
13. Post-Quantum (2023) Google Claims Breakthrough in Quantum Error Correction. Available at: https://postquantum.com/quantum-research/google-breakthrough-error-correction/
14. Google (2025) Our Quantum Echoes algorithm is a big step toward real-world applications for quantum computing. Available at: https://blog.google/technology/research/quantum-echoes-willow-verifiable-quantum-advantage/
15. Arute, F. et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature. Available at: https://www.nature.com/articles/s41586-019-1666-5
16. Google Quantum AI (2023) Suppressing quantum errors by scaling a surface code logical qubit. Nature. Available at: https://www.nature.com/articles/s41586-022-05434-1
17. Google Quantum AI (2023) Suppressing quantum errors by scaling a surface code logical qubit. Available at: https://research.google/blog/suppressing-quantum-errors-by-scaling-a-surface-code-logical-qubit/
18. Google Quantum AI (2025) Google Quantum AI. Available at: https://quantumai.google/
19. Reuters (2025) AI startup SandboxAQ adds NVIDIA, Google as backers, raises additional $150 million. Available at: https://www.reuters.com/technology/artificial-intelligence/ai-startup-sandboxaq-adds-NVIDIA-google-backers-raises-additional-150-million-2025-04-04/
20. Reuters (2025) Quantum-computing startup QuEra closes US$230 million funding round. Available at: https://www.reuters.com/technology/quantum-computing-startup-quera-closes-230-million-funding-round-2025-02-11/
21. Rigetti Computing (2024) Rigetti Computing launches 84-Qubit Ankaa™-3 System; achieves 99.5% median two-qubit gate fidelity milestone. Available at: https://www.globenewswire.com/news-release/2024/12/23/3001239/0/en/Rigetti-Computing-Launches-84-Qubit-Ankaa-3-System-Achieves-99-5-Median-Two-Qubit-Gate-Fidelity-Milestone.html
22. AWS. Rigetti – Amazon Braket Quantum Computers. Available at: https://aws.amazon.com/braket/quantum-computers/rigetti/
23. Rigetti Computing. Applications. Available at: https://www.rigetti.com/applications
24. Rigetti Computing (2025) Rigetti Computing Reports Fourth Quarter and Full-Year 2024 Results. Available at: https://investors.rigetti.com/news-releases/news-release-details/rigetti-computing-reports-fourth-quarter-and-full-year-2024
25. Fujitsu (2025) Fujitsu and RIKEN develop world-leading 256-qubit superconducting quantum computer. Available at: https://www.fujitsu.com/global/about/resources/news/press-releases/2025/0422-01.html
26. RIKEN (2025) RIKEN and Fujitsu unveil world-leading 256-qubit quantum computer. Available at: https://www.riken.jp/en/news_pubs/news/2025/20250422_1/index.html
27. DataCenterDynamics (2025) Fujitsu begins development of 10,000-plus qubit quantum computer. Available at: https://www.datacenterdynamics.com/en/news/fujitsu-begins-development-of-10000-plus-qubit-quantum-computer/

28. China State Council (2025) China hits new landmark in global quantum computing race. Available at: https://english.www.gov.cn/news/202503/04/content_WS67c656dbc6d0868f4e8f0489.html
29. China Daily (2025) China's superconducting quantum computer ready for commercial use. Available at: https://global.chinadaily.com.cn/a/202510/12/WS68eb6e3aa310f735438b47fc.html
30. University of Science and Technology of China (2025) Zuchongzhi-3: A 105-Qubit Superconducting Quantum Processor with 10^{15} Times Speedup in Circuit Sampling. Available at: https://en.ustc.edu.cn/info/1007/5015.htm
31. APS Journals (2025) Establishing a New Benchmark in Quantum Computational Advantage with 105-qubit Zuchongzhi 3.0 Processor. Available at: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.134.090601
32. Tan He et al., "Experimental Quantum Error Correction below the Surface Code Threshold via All-Microwave Leakage Suppression," Physical Review Letters 135, no. 26 (2025). Available at: https://doi.org/10.1103/rqkg-dw31
33. D-Wave. Advantage2 System: Our Most Advanced and Performant Quantum Computer. Available at: https://www.dwavequantum.com/solutions-and-products/systems/
34. D-Wave. Quantum Optimization. Available at: https://www.dwavequantum.com/solutions-and-products/quantum-optimization/quantum-optimization-landing-page/
35. D-Wave (2020) D-Wave Hybrid Solver Service: An Overview. Available at: https://www.dwavequantum.com/media/4bnpi53x/14-1039a-b_d-wave_hybrid_solver_service_an_overview.pdf
36. McGeoch (2020). Theory versus Practice in Annealing-Based Quantum Computing, Theoretical Computer Science, 816 (May 2020): 169–183. Available at: https://doi.org/10.1016/j.tcs.2020.01.024
37. Pascal (2024) Pasqal announces New Roadmap focused on Business Utility and Scaling beyond 1,000 Qubits towards Fault Tolerance Era. Available at: https://www.pasqal.com/newsroom/pasqal-announces-new-roadmap-focused-on-business-utility-and-scaling-beyond-1000-qubits-towards-fault-tolerance-era/
38. Atom Computing (2025) Atom Computing selected by DARPA for the next stage of exploring near-term utility-scale quantum computing with neutral atoms. Available at: https://atom-computing.com/atom-computing-selected-by-darpa-for-the-next-stage-of-exploring-near-term-utility-scale-quantum-computing-with-neutral-atoms/
39. Quantum Computing Report (2025) Quantinuum Achieves Quantum Volume of 2^{25} on System Model H2. Available at: https://quantumcomputingreport.com/quantinuum-achieves-quantum-volume-of-2%C2%B2%E2%81%B5-on-system-model-h2/; Quantinuum (2025) Quantum Volume. Available at: https://www.quantinuum.com/glossary-item/quantum-volume
40. Quantinuum (2025) Quantinuum extends its significant lead in quantum computing, achieving historic milestones for hardware fidelity and quantum volume. Available at: https://www.quantinuum.com/blog/quantinuum-extends-its-significant-lead-in-quantum-computing-achieving-historic-milestones-for-hardware-fidelity-and-quantum-volume; Quantinuum (2025) Quantinuum and Microsoft announce new era in quantum computing with breakthrough demonstration of reliable qubits. Available at: https://www.quantinuum.com/press-releases/quantinuum-and-microsoft-announce-new-era-in-quantum-computing-with-breakthrough-demonstration-of-reliable-qubits
41. Quantinuum (2025) Quantinuum System Model H2. Available at: https://www.quantinuum.com/products-solutions/quantinuum-systems/system-model-h2
42. Reuters (2025) Honeywell's Quantinuum raises funds from NVIDIA, others at $10 billion valuation. Available at: https://www.reuters.com/business/honeywells-quantinuum-raises-funds-NVIDIA-others-10-billion-valuation-2025-09-04/
43. IonQ (2025) IonQ Achieves Record-Breaking Quantum Performance Milestone of #AQ 64. Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Achieves-Record-Breaking-Quantum-Performance-Milestone-of-AQ-64/default.aspx
44. PostQuantum (2025) IonQ's 2025 Roadmap: Toward a Cryptographically Relevant Quantum Computer by 2028. Available at: https://postquantum.com/industry-news/ionqroadmap-crqc/
45. IonQ (2025) IonQ Completes Acquisition of Oxford Ionics, Rapidly Accelerating Its Quantum Computing Roadmap. Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Completes-Acquisition-of-Oxford-Ionics-Rapidly-Accelerating-Its-Quantum-Computing-Roadmap/default.aspx
46. IonQ (2025) IonQ Completes Acquisition of ID Quantique, Cementing Leadership in Quantum Networking and Secure Communications. Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Completes-Acquisition-of-ID-Quantique-Cementing-Leadership-in-Quantum-Networking-and-Secure-Communications/default.aspx
47. IonQ (2025) IonQ Advances to Stage B of DARPA's Quantum Benchmarking Initiative (QBI). Available at: https://investors.ionq.com/news/news-details/2025/IonQ-Advances-to-Stage-B-of-DARPAs-Quantum-Benchmarking-Initiative-QBI/default.aspx

48. PsiQuantum (2025) PsiQuantum Raises $1 B to Build Million-Qubit Scale, Fault-Tolerant Quantum Computers. Available at: https://www.psiquantum.com/news-import/psiquantum-1b-fundraise
49. PsiQuantum (2025) PsiQuantum raises $1 billion in Series E funding — NVIDIA, BlackRock among backers. Available at: https://www.siliconrepublic.com/start-ups/psiquantum-1bn-raise-NVIDIA-blackrock-quantum-chips-manufacturing
50. IEEE Spectrum (2025) PsiQuantum Plans Quantum Supercomputer That Runs on Light. Available at: https://spectrum.ieee.org/psiquantum-supercomputer
51. Xanadu (2025) Xanadu introduces Aurora: world's first scalable, networked and modular quantum computer. Available at: https://www.xanadu.ai/press/xanadu-introduces-aurora-worlds-first-scalable-networked-and-modular-quantum-computer
52. Xanadu (2025) Xanadu unveils Aurora: the world's first scalable photonic quantum computer. Available at: https://www.innovationnewsnetwork.com/xanadu-unveils-aurora-the-worlds-first-scalable-photonic-quantum-computer/54880/
53. Quantum Insider (2025). BTQ Launches Quantum Proof-of-Work Simulator, Delivering Demonstration of Quantum Advantage in Blockchain Consensus. Available at: https://thequantuminsider.com/2025/07/08/btq-launches-quantum-proof-of-work-simulator-delivering-demonstration-of-quantum-advantage-in-blockchain-consensus/
54. PR Newswire (2025) BTQ and ICTK Sign USD 15M Quantum-Secure Chip Development and Joint Investment Agreement to Advance Global Quantum-Safe Hardware. Available at: https://www.prnewswire.com/news-releases/btq-and-ictk-sign-usd-15m-quantum-secure-chip-development-and-joint-investment-agreement-to-advance-global-quantum-safe-hardware-302595200.html
55. Intel (2025) Researchers progress with Tunnel Falls. Available at: https://www.intel.com/content/www/us/en/research/overview.html
56. Microsoft (2025) Microsoft achieves important milestone toward topological qubits. Available at: https://techcommunity.microsoft.com/t5/azure-quantum-blog/microsoft-achieves-important-milestone-toward-topological-qubits/ba-p/4086892
57. The Quantum Insider (2025) Quantum Computing Roadmaps: A Look at The Maps And Predictions of Major Players. Available at: https://thequantuminsider.com/2025/05/16/quantum-computing-roadmaps-a-look-at-the-maps-and-predictions-of-major-quantum-players/
58. NVIDIA (2025) Introducing NVIDIA CUDA-Q: The Platform for Hybrid Quantum-Classical Computing. Available at: https://developer.NVIDIA.com/blog/introducing-cuda-quantum-the-platform-for-hybrid-quantum-classical-computing
59. NextPlatform (2025) NVIDIA Research: The Real Reason Big Green Commands Big Profits. Available at: https://www.nextplatform.com/2025/03/30/NVIDIA-research-the-real-reason-big-green-commands-big-profits/
60. AWS Blogs (2024) AWS announces the Quantum Embark Program to help customers get ready for quantum computing. Available at: https://aws.amazon.com/blogs/quantum-computing/aws-announces-the-quantum-embark-program-to-help-customers-get-ready-for-quantum-computing/
61. Quantum Logistics (2021) DHL Supply Chain and D-Wave Trial Quantum Annealing for Warehouse Routing Efficiency. Available at: https://www.quantumlogistics.com/articles2021/15/04222021
62. D-Wave (2024) Tackling route complexity: Quantum optimization for efficient, scalable logistics. Available at: https://www.dwavequantum.com/media/t5be11b4/logistics-routing-data-sheet.pdf
63. D-Wave (2023) D-Wave announces new commercial customer engagements, cross-platform product enhancements at Qubits 2023. Available at: https://www.dwavequantum.com/company/newsroom/press-release/d-wave-announces-new-commercial-customer-engagements-cross-platform-product-enhancements-at-qubits-2023/
64. IBM (2025) HSBC breaks new ground in quantum-enabled algorithmic trading with IBM quantum computers. Available at: https://www.ibm.com/quantum/blog/hsbc
65. Business Insider (2025) AI startup SandboxAQ adds NVIDIA, Google as backers, raises additional $150 million. Available at: https://www.businessinsider.com/quantum-computing-financial-markets-portfolio-optimization-vanguard-ibm-hsbc-2025-10
66. Pramanik, S. et al. (2022) Optimization of Sensor-Placement on Vehicles using Quantum-Classical Hybrid Methods. arXiv. Available at: https://arxiv.org/abs/2206.14546
67. University of Missouri (2024) Mizzou establishes IBM Quantum Innovation Center. Available at: https://engineering.missouri.edu/2024/mizzou-establishes-ibm-quantum-innovation-center/
68. InvestorBrandNetwork (2025) D-Wave Quantum Inc. (NYSE: QBTS). Available at: https://www.investorbrandnetwork.com
69. McKinsey (2025) The Year of Quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
70. University of Sydney (2025) Quantum simulation of chemical dynamics achieved for the first time. Available at: https://www.sydney.edu.au/news-opinion/news/2025/05/15/quantum-simulation-of-chemical-dynamics-achieved-for-the-first-t.html

71. MIT (2025) Quantum modeling for breakthroughs in materials science and sustainable energy. Available at: https://news.mit.edu/2025/quantum-modeling-breakthroughs-materials-science-sustainable-energy-ernest-opoku-1119
72. SpinQ (2025) Quantum Computing Industry Trends 2025: A Year of Breakthrough Milestones and Commercial Transition. Available at: https://www.spinquanta.com/news-detail/quantum-computing-industry-trends-2025-breakthrough-milestones-commercial-transition
73. IntuitionLabs (2025) IBM Quantum's Role in Pharmaceutical Drug Discovery. Available at: https://intuitionlabs.ai/pdfs/ibm-quantum-s-role-in-pharmaceutical-drug-discovery.pdf
74. The Quantum Insider (2025) Cleveland Clinic and IBM Use Hybrid Quantum Computing to Simulate Molecules. Available at: https://thequantuminsider.com/2025/11/19/cleveland-clinic-ibm-hybrid-quantum-molecule-simulation/
75. Quantum Computing Report (2025) IonQ and Ansys demonstrate quantum speedup in engineering simulation workflow. Available at: https://quantumcomputingreport.com/ionq-and-ansys-demonstrate-quantum-speedup-in-engineering-simulation-workflow/
76. The Quantum Insider (2025) IonQ's devices boost Ansys simulations, achieving up to 12% faster processing over classical computers. Available at: https://thequantuminsider.com/2025/03/20/ionqs-devices-boost-ansys-simulations-achieving-up-to-12-faster-processing-over-classical-computers/
77. SpinQ (2025) Quantum Computing as a Service: Use Cases and Benefits. Available at: https://www.spinquanta.com/news-detail/quantum-computing-as-a-service
78. IBM. https://www.ibm.com/quantum/products
79. Live Science (2025) 'The science is solve: IBM to build monster 10,000-qubit quantum computer by 2029 after solving science behind fault tolerance'. Available at: https://www.livescience.com/technology/computing/ibm-will-build-monster-10-000-qubit-quantum-computer-by-2029-after-solving-science-behind-fault-tolerance
80. Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/
81. Deloitte (2025) 'Quantum computing futures', Deloitte Insights, 11 August. Available at: https://www.deloitte.com/us/en/insights/topics/emerging-technologies/quantum-computing-futures.html
82. McKinsey & Company (2025) The quantum revolution in pharma: Faster, smarter, and more precise. Available at: https://www.mckinsey.com/industries/life-sciences/our-insights/the-quantum-revolution-in-pharma-faster-smarter-and-more-precise
83. Boston Consulting Group (2024) Quantum Computing On Track to Create Up to US$850 Billion of Economic Value by 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040
84. McKinsey & Company (2025) The year of quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
85. Bank of Finland (2025) Quantum computing is coming – Is the financial sector ready? Available at: https://www.bofbulletin.fi/en/2025/articles/quantum-computing-is-coming-is-the-financial-sector-ready/
86. The Quantum Insider (2024) New Study from JPMorgan Chase and AWS Optimizes Large-Scale Portfolio Management with Quantum-Classical Hybrid Solutions. Available at: https://thequantuminsider.com/2024/09/19/new-study-from-jpmorgan-chase-and-aws-optimizes-large-scale-portfolio-management-with-quantum-classical-hybrid-solutions/
87. FStech (2024) Goldman Sachs works with quantum scale-up to research options pricing algorithm. Available at: https://www.fstech.co.uk/fst/Goldman_Sachs_Works_With_Quantum_Scale_Up_To_Research_Options_Pricing_Algorithm.php
88. The Quantum Insider (2025) New Quantum Index Monitors Progress in Life-Sciences Demand for Quantum Tools. Available at: https://thequantuminsider.com/2025/05/08/new-quantum-index-monitors-progress-in-life-sciences-demand-for-quantum-tools/
89. IntuitionLabs.ai (2025) IBM Quantum's Role in Pharmaceutical Drug Discovery. Available at: https://intuitionlabs.ai/pdfs/ibm-quantum-s-role-in-pharmaceutical-drug-discovery.pdf
90. World Economic Forum (2025) Quantum Technologies: Key Opportunities for Advanced Manufacturing and Supply Chains. Available at: https://www.weforum.org/publications/quantum-technologies-key-opportunities-for-advanced-manufacturing-and-supply-chains/
91. Airbus (2024) Quantum Leaps: Winners of Airbus and BMW Group's Quantum Computing Challenge Unveiled. Available at: https://www.airbus.com/en/newsroom/press-releases/2024-12-quantum-leaps-winners-of-airbus-and-bmw-groups-quantum-computing

92. EQMagPro (2019) Mercedes enlists quantum computing to build a better electric vehicle battery. Available at: https://www.eqmagpro.com/mercedes-enlists-quantum-computing-to-build-a-better-electric-vehicle-battery/
93. Munich Re (2021) Quantum Technology and Application Consortium (QUTAC): Munich Re participates in the establishment of the new consortium. Available at: https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/corporate-news/2021/2021-06-10-qutac.html
94. D-Wave Quantum Inc. (2025) BASF and D-Wave announce completion of proof-of-concept project, demonstrating benchmark in manufacturing efficiency. Available at: https://www.dwavequantum.com/company/newsroom/press-release/basf-and-d-wave-announce-completion-of-proof-of-concept-project-demonstrating-benchmark-in-manufacturing-efficiency/
95. Safety4Sea (2019) ExxonMobil, IBM to promote quantum computing for energy sector. Available at: https://safety4sea.com/exxonmobil-ibm-to-promote-quantum-computing-for-energy-sector/
96. The Quantum Insider (2021) BP's partnership with the IBM Quantum Network out to reduce carbon emissions. Available at: https://thequantuminsider.com/2021/02/21/bps-partnership-with-the-ibm-quantum-network-out-to-reduce-carbon-%E2%80%8Eemissions/
97. Department of Energy / Potomac Officers Club (2021) DOE awards fusion energy quantum computing project to Rigetti. Available at: https://www.potomacofficersclub.com/news/doe-awards-fusion-energy-quantum-computing-project-to-rigetti/
98. Boston Consulting Group (2024) Quantum Computing On Track to Create Up to US$850 Billion of Economic Value by 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040
99. IBM (2025) How IBM will build the world's first large-scale, fault-tolerant quantum computer. Available at: https://www.ibm.com/quantum/blog/large-scale-ftqc
100. IonQ (2025) IonQ Demonstrates Quantum-Enhanced Applications Advancing AI. Available at: https://ionq.com/news/ionq-demonstrates-quantum-enhanced-applications-advancing-ai
101. D-Wave Quantum (2025) D-Wave Introduces Quantum Blockchain Architecture, Featuring Enhanced Security and Efficiency over Classical Computing. Available at: https://www.dwavequantum.com/company/newsroom/press-release/d-wave-introduces-quantum-blockchain-architecture-featuring-enhanced-security-and-efficiency-over-classical-computing/
102. Eq-Mag Pro (2019) Mercedes enlists quantum computing to build a better electric vehicle battery. Available at: https://www.eqmagpro.com/mercedes-enlists-quantum-computing-to-build-a-better-electric-vehicle-battery/
103. EE Times Europe (2024) BASF and Kipu Focus on End-User Mastery of Quantum Computing. Available at: https://www.eetimes.eu/basf-and-kipu-focus-on-end-user-mastery-of-quantum-computing/
104. FutureMarketInsights (2025) Post-Quantum Cryptography (PQC) Migration Market. Available at: https://www.futuremarketinsights.com/reports/post-quantum-cryptography-pqc-migration-market
105. The Quantum Insider (2025) UK Sets Timeline, Road Map for Post-Quantum Cryptography Migration. Available at: https://thequantuminsider.com/2025/03/20/uk-sets-timeline-road-map-for-post-quantum-cryptography-migration/
106. CoinLaw (2025) Quantum Cryptography in Finance Statistics 2025: How Quantum Cryptography is Transforming the Industry. Available at: https://coinlaw.io/quantum-cryptography-in-finance-statistics/
107. SNS Insider (2025) Quantum Key Distribution Market Report. Available at: https://www.snsinsider.com/reports/quantum-key-distribution-market-8738
108. LiveScience (2025) New semiconductor could allow classical and quantum computing on the same chip, thanks to superconductivity breakthrough. Available at: https://www.livescience.com/technology/computing/new-semiconductor-could-allow-classical-and-quantum-computing-on-the-same-chip-thanks-to-superconductivity-breakthrough
109. Innovation News Network (2025) Quantum sensors will power $2.2bn tech revolution by 2045. Available at: https://www.innovationnewsnetwork.com/quantum-sensors-will-power-2-2bn-tech-revolution-by-2045/
110. Barends R, Kelly J, Megrant A et al. (2014) Superconducting quantum circuits at the surface code threshold for fault tolerance. Nature 508, 500–503. Available at: https://www.nature.com/articles/nature13171
111. IBM (2021) Five years ago today, we put the first quantum computer on the cloud. Here's how we did it. Available at: https://www.ibm.com/quantum/blog/quantum-five-years
112. Arute, F., Brandão, F. G. S. L., et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510. Available at: https://www.nature.com/articles/s41586-019-1666-5
113. IonQ. Resources. Available at: https://ionq.com/resources
114. Xanadu (2020) Xanadu brings photonic quantum computing to the cloud. Available at: https://www.xanadu.ai/press/xanadu-brings-photonic-quantum-computing-to-the-cloud
115. IBM (2021) IBM Quantum breaks the 100-qubit processor barrier: 127-qubit "Eagle" quantum processor unveiled. Available at: https://www.ibm.com/quantum/blog/127-qubit-quantum-processor-eagle

116. IBM (2023) IBM Unveils Quantum Roadmap Through 2033. Available at: https://www.ibm.com/quantum/blog/quantum-roadmap-2033
117. PostQuantum.com (2024) Microsoft Announces Record Breaking Logical Qubit Results. Available at: https://postquantum.com/industry-news/logical-qubit-microsoft/
118. PsiQuantum (2025) PsiQuantum Raises $1 Billion to Build Million-Qubit Scale, Fault-Tolerant Quantum Computers. Available at: https://www.psiquantum.com/news-import/psiquantum-1b-fundraise
119. Xanadu (2025) Xanadu unveils first on-chip error-resistant photonic qubit. Available at: https://www.xanadu.ai/press/xanadu-unveils-first-on-chip-error-resistant-photonic-qubit/
120. Google (2025) Our Quantum Echoes algorithm is a big step toward real-world applications for quantum computing. Available at: https://blog.google/technology/research/quantum-echoes-willow-verifiable-quantum-advantage/
121. Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/
122. Google DeepMind (2024) AlphaQubit: Google's research on quantum error correction. Available at: https://blog.google/technology/google-deepmind/alphaqubit-quantum-error-correction/
123. IBM (2025) IBM delivers new quantum processors, software, and algorithm breakthroughs on path to advantage and fault tolerance. Available at: https://newsroom.ibm.com/2025-11-12-ibm-delivers-new-quantum-processors,-software,-and-algorithm-breakthroughs-on-path-to-advantage-and-fault-tolerance
124. IonQ (2024) IonQ Achieves Industry Breakthrough – First Trapped Ion Quantum System to Surpass 99.9% Fidelity on Barium. Available at: https://ionq.com/news/ionq-achieves-industry-breakthrough-first-trapped-ion-quantum-system-to
125. Quantinuum (2023) Quantinuum's H1 quantum computer successfully executes a fully fault-tolerant algorithm with three logically-encoded qubits. Available at: https://www.quantinuum.com/press-releases/quantinuums-h1-quantum-computer-successfully-executes-a-fully-fault-tolerant-algorithm-with-three-logically-encoded-qubits
126. MarketsandMarkets (2025) Quantum Computing Market Size, Share & Trends. Available at: https://www.marketsandmarkets.com/Market-Reports/quantum-computing-market-144888301.html
127. McKinsey & Company (2025) The Year of Quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
128. The Rapacke Law Group (2025) Top Quantum Computing Patents: Trends, Players, and Innovations in 2025. Available at: https://arapackelaw.com/patents/quantum-computing-patents/
129. Google Quantum AI and Collaborators (2025) Quantum error correction below the surface code threshold. Available at: https://www.nature.com/articles/s41586-024-08449-y
130. Microsoft (2025) Quantum Error Correction. Available at: https://quantum.microsoft.com//en-us/insights/education/concepts/quantum-error-correction
131. SingularityHub (2023) IBM Is Planning to Build Its First Fault-Tolerant Quantum Computer by 2029. Available at: https://singularityhub.com/2023/12/06/ibm-is-planning-to-build-its-first-fault-tolerant-quantum-computer-by-2029/
132. postquantum.com (2025) IBM. Available at: https://postquantum.com/quantum-computing-companies/ibm/
133. PostQuantum (2025) IonQ's 2025 Roadmap: Toward a Cryptographically Relevant Quantum Computer by 2028. Available at: https://postquantum.com/industry-news/ionqroadmap-crqc/
134. Raigada García, R. S. (2024) Quantum Error Correction Below the Surface Code Threshold. Available at: https://openaccess.uoc.edu/server/api/core/bitstreams/fef50b85-661c-430f-9a89-3711f8ce5fca/content
135. Acharya, R. et al. (2022) Suppressing quantum errors by scaling a surface code logical qubit. arXiv:2207.06431. Available at: https://arxiv.org/abs/2207.06431
136. The Verge (2024) Google reveals quantum computing chip with 'breakthrough' achievements. Available at: https://www.theverge.com/2024/12/9/24317382/google-willow-quantum-computing-chip-breakthrough
137. Reuters (2024) Microsoft, Quantinuum claim breakthrough in quantum computing. Available at: https://www.reuters.com/technology/microsoft-quantinuum-claim-breakthrough-quantum-computing-2024-04-03/
138. Quantinuum (2022) Logical qubits start outperforming physical qubits. Available at: https://www.quantinuum.com/press-releases/logical-qubits-start-outperforming-physical-qubits
139. IBM Quantum (2024) IBM Quantum Development & Innovation Roadmap – 2024 Update. Available at: https://www.ibm.com/quantum/assets/IBM_Quantum_Developmen_&_Innovation_Roadmap_Explainer_2024-Update.pdf
140. Quantum Computing Report (2025) IBM reveals more details about its quantum error correction roadmap. Available at: https://quantumcomputingreport.com/ibm-reveals-more-details-about-its-quantum-error-correction-roadmap/
141. IBM Quantum (2024) IBM Quantum Development & Innovation Roadmap – 2024 Update. Available at: https://www.ibm.com/quantum/assets/IBM_Quantum_Developmen_&_Innovation_Roadmap_Explainer_2024-Update.pdf
142. NVIDIA DGX H100 — NVIDIA (2025) DGX H100. Available at: https://www.NVIDIA.com/en-us/data-center/dgx-h100/

143. Arute, F. et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510. Available at: https://www.nature.com/articles/s41586-019-1666-5
144. Arute, F. et al. (2019) Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510. Available at: https://www.nature.com/articles/s41586-019-1666-5
145. ScienceDirect. Intel Architecture (IA). Available at: https://www.sciencedirect.com/topics/computer-science/intel-architecture
146. AMD. AMD "Zen" Core Architecture. Available at: https://www.amd.com/en/technologies/zen
147. NVIDIA DGX H100 — NVIDIA (2025) DGX H100. Available at: https://www.NVIDIA.com/en-us/data-center/dgx-h100/
148. NVIDIA. CUDA Zone. Available at: https://developer.NVIDIA.com/cuda
149. Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/
150. McKinsey & Company (2025) The Year of Quantum: From Concept to Reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
151. World Economic Forum (2025) Quantum Technologies: Key Opportunities for Advanced Manufacturing and Supply Chains. Available at: https://www.weforum.org/publications/quantum-technologies-key-opportunities-for-advanced-manufacturing-and-supply-chains/
152. ScienceDirect. Intel Architecture (IA). Available at: https://www.sciencedirect.com/topics/computer-science/intel-architecture
153. NVIDIA. CUDA Zone. Available at: https://developer.NVIDIA.com/cuda
154. NVIDIA DGX H100 — NVIDIA (2025) DGX H100. Available at: https://www.NVIDIA.com/en-us/data-center/dgx-h100/
155. Boston Consulting Group (2024) Quantum Computing On Track to Create Up to US$850 Billion of Economic Value by 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040
156. EQ Mag Pro (2019) Mercedes Enlists Quantum Computing to Build a Better Electric Vehicle Battery. Available at: https://www.eqmagpro.com/mercedes-enlists-quantum-computing-to-build-a-better-electric-vehicle-battery/
157. FutureMarketInsights (2025) Post-Quantum Cryptography (PQC) Migration Market. Available at: https://www.futuremarketinsights.com/reports/post-quantum-cryptography-pqc-migration-market
158. The Quantum Insider (2025) UK Sets Timeline, Road Map for Post-Quantum Cryptography Migration. Available at: https://thequantuminsider.com/2025/03/20/uk-sets-timeline-road-map-for-post-quantum-cryptography-migration/
159. IonQ (2025) IonQ Demonstrates Quantum-Enhanced Applications Advancing AI. Available at: https://ionq.com/news/ionq-demonstrates-quantum-enhanced-applications-advancing-ai
160. Investopedia(2025). How NVIDIA Makes Money. Available at: https://www.investopedia.com/how-NVIDIA-makes-money-4799532
161. McKinsey (2025) The Year of Quantum: From concept to reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
162. NVIDIA. CUDA Zone. Available at: https://developer.NVIDIA.com/cuda
163. Classiq (2025) Researchers Poised for Advances With NVIDIA CUDA-Q. Available at: https://www.classiq.io/insights/researchers-poised-for-advances-with-NVIDIA-cuda-quantum
164. Classiq (2025) Researchers Poised for Advances With NVIDIA CUDA-Q. Available at: https://www.classiq.io/insights/researchers-poised-for-advances-with-NVIDIA-cuda-quantum
165. NVIDIA (2022) Introducing NVIDIA CUDA-Q: The Platform for Hybrid Quantum-Classical Computing. Available at: https://developer.NVIDIA.com/blog/introducing-cuda-quantum-the-platform-for-hybrid-quantum-classical-computing/
166. NVIDIA. High-Performance Computing. Available at: https://www.NVIDIA.com/en-gb/high-performance-computing/
167. NVIDIA (2022) NVIDIA Announces Hybrid Quantum-Classical Computing Platform. Available at: https://NVIDIAnews.NVIDIA.com/news/NVIDIA-announces-hybrid-quantum-classical-computing-platform
168. IonQ (2024) IonQ to Advance Hybrid Quantum Computing with New Chemistry Application and NVIDIA CUDA-Q. Available at: https://ionq.com/news/ionq-to-advance-hybrid-quantum-computing-with-new-chemistry-application-and
169. McKinsey & Company (2025) The Year of Quantum: From Concept to Reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
170. U.S. Department of Energy (2025) Energy Department announces US$ 625 million to advance next phase of National Quantum Information Science Research Centers. Available at: https://www.energy.gov/articles/energy-department-announces-625-million-advance-next-phase-national-quantum-information
171. Ames National Laboratory (2025) DOE renews SQMS Center with US$ 125 million to advance quantum technologies. Available at: https://www.ameslab.gov/news/doe-renews-sqms-center-with-125-million-to-advance-quantum-technologies

172. Argonne National Laboratory / Fermilab (2022) Quantum network between two national labs achieves record synch. Available at:https://www.anl.gov/article/quantum-network-between-two-national-labs-achieves-record-synch
173. Fermilab / IEQnet (n.d.) IEQnet: Fermilab's Quantum-Networking Project. Available at: https://ieqnet.fnal.gov/
174. Fermilab (2023) Fermilab receives DOE funding to further develop nationwide quantum network. Available at: https://news.fnal.gov/2023/10/fermilab-receives-doe-funding-to-further-develop-nationwide-quantum-network/
175. United States Congress (2022) Quantum Computing Cybersecurity Preparedness Act (H.R. 7535). Available at: https://www.congress.gov/bill/117th-congress/house-bill/7535
176. Office of Management and Budget (2023) M-24-08: Strengthening Digital Accessibility and the Management of Section 508 of the Rehabilitation Act. Available at: https://www.whitehouse.gov/wp-content/uploads/2023/12/M-24-08-Strengthening-Digital-Accessibility-and-the-Management-of-Section-508-of-the-Rehabilitation-Act.pdf
177. The White House (2025) National Security Strategy of the United States of America. Available at: https://www.whitehouse.gov/wp-content/uploads/2025/12/2025-National-Security-Strategy.pdf
178. eoPortal (2025) QUESS. Available at: https://www.eoportal.org/satellite-missions/quess
179. Yin, J. et al. (2017) Satellite-Based Entanglement Distribution Over 1200 Kilometers. Available at: https://arxiv.org/pdf/1707.01339
180. Chinese Academy of Sciences (2017) China's quantum satellite establishes photon entanglement over 1,200 km. Available at: https://english.cas.cn/newsroom/archive/news_archive/nu2017/201703/t20170324_175288.shtml
181. University of Science and Technology of China (USTC) (2021) The world's first integrated quantum communication network. Available at: https://en.ustc.edu.cn/info/1007/3182.htm
182. ITIF (2024) How Innovative Is China in Quantum? Available at: https://itif.org/publications/2024/09/09/how-innovative-is-china-in-quantum/
183. Information Technology & Innovation Foundation (ITIF) (2024) How Innovative Is China in Quantum? Available at: https://itif.org/publications/2024/09/09/how-innovative-is-china-in-quantum/
184. MSN (2025) China is no longer a follower in the race for quantum supremacy. Available at: https://www.msn.com/en-xl/news/other/china-is-no-longer-a-follower-in-the-race-for-quantum-supremacy/ar-AA1Sbg14
185. European Commission (n.d.) EU Quantum Technologies Flagship. Available at: https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship
186. Quantum Flagship. Quantum Flagship. Available at: https://qt.eu/
187. CIFAR (2021) A Quantum Revolution: Report on Global Policies for Quantum Technology. Available at: https://cifar.ca/wp-content/uploads/2021/05/quantum-report-EN-11-accessible.pdf
188. Federal Ministry of Education and Research (BMBF) (2022) Bekanntmachung: Quantencomputing-Förderung Deutschland. Available at: https://www.bmftr.bund.de/SharedDocs/Bekanntmachungen/DE/2021/05/3591_bekanntmachung.html
189. EE Times Europe (2021) French President details €1.8 billion quantum plan. Available at: https://www.eetimes.eu/french-president-details-e1-8b-quantum-plan/
190. Quantum Delta NL (n.d.) Quantum Delta NL Programme. Available at: https://quantumdelta.nl/programme-overview
191. VTT Technical Research Centre of Finland (VTT) (2025) VTT and IQM launch first 50-qubit quantum computer developed in Europe. Available at: https://www.vttresearch.com/en/news-and-ideas/vtt-and-iqm-launch-first-50-qubit-quantum-computer-developed-europe
192. UK Government (2023) New technologies on show at Quantum Showcase as Science Minister drives forward UK's £2.5 billion Quantum Strategy. Available at: https://www.gov.uk/government/news/new-technologies-on-show-at-quantum-showcase-as-science-minister-drives-forward-uks-25-billion-quantum-strategy
193. European Commission (n.d.) EU Cybersecurity Act. Available at: https://digital-strategy.ec.europa.eu/en/policies/cybersecurity-act
194. ETSI (2025) Industry Specification Group (ISG) on Quantum Key Distribution (QKD). Available at: https://www.etsi.org/committee/qkd
195. European Commission (2025) European Quantum Communication Infrastructure (EuroQCI). Available at: https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci
196. EU Agency for the Space Programme (2025) EU-Space Programme: Prepare Quantum Future. Available at: https://www.euspa.europa.eu/newsroom-events/news
197. RIKEN (2022) Quantum technology policy in Japan. Available at: https://quantum-innovation.riken.jp/archives/QI2022/program/pdf/PL-02-01.pdf
198. Institute of Geoeconomics (2025) Japan needs to take the quantum-technology leap. Available at: https://quantum-innovation.riken.jp/archives/QI2022/program/pdf/PL-02-01.pdf

199. QuantumComputer.blog (2025) Quantum AI Japan Government Unveil ¥400 B Budget for Fusion. Available at: https://quantumcomputer.blog/quantum-ai-japan-unveil-%C2%A5400-b-budget-fusion/
200. Fujitsu (2025) Fujitsu Strengthens Global Quantum-Safe Cryptography Efforts. Available at: https://www.fujitsu.com/global/about/resources/news/press-releases/2025/0422-01.html
201. LiveScience (2025) Japan launches its first homegrown quantum computer. Available at: https://www.livescience.com/technology/computing/japan-launches-its-first-homegrown-quantum-computer
202. UK RI (2025) Japan-UK Joint Call for Quantum Technologies for Innovation. Available at: https://www.ukri.org/opportunity/japan-uk-joint-call-for-quantum-technologies-for-innovation/
203. Ministry of Science and ICT (MSIT) (2023) In 2035, Korea Becoming the Global Hub for Quantum Economy! Available at: https://www.msit.go.kr/eng/bbs/view.do?bbsSeqNo=42&mId=4&mPid=2&nttSeqNo=828&sCode=eng&searchOpt=ALL
204. The Quantum Insider (2023) South Korea to Invest $2.33 Billion in Quantum by 2035. Available at: https://thequantuminsider.com/2023/06/29/south-korea-to-invest-2-33-billion-in-quantum-by-2035/
205. Reuters (2025) South Korea prepares $34 bln fund for national strategic industries. Available at: https://www.reuters.com/markets/asia/south-korea-prepares-34-bln-fund-national-strategic-industries-2025-03-05/
206. RSIS (2025) Singapore's National Quantum Strategy Turns One. Available at: https://rsis.edu.sg/rsis-publication/idss/ip25069-singapores-national-quantum-strategy-turns-one/
207. The Quantum Insider (2024) Singapore Invests S$300 Million in National Quantum Strategy. Available at: https://thequantuminsider.com/2024/05/30/singapore-invests-s300-million-in-national-quantum-strategy/
208. National Quantum Office (2024) Close to S$300 million invested to drive Singapore's National Quantum Strategy over five years. Available at: https://nqo.sg/wp-content/uploads/2024/06/Media-Factsheet_NQO_National-Quantum-Strategy_27-May-clean-1.pdf
209. Centre for Quantum Technologies (2025) CQT updates roles in national quantum programmes. Available at: https://www.cqt.sg/highlight/2025-06-national-quantum-programmes/
210. National Quantum Office (2025) National Quantum Office. Available at: https://nqo.sg/
211. Centre for Quantum Technologies (2025) Singapore's National Quantum Office and Quantinuum Forge Strategic Partnership to Accelerate Quantum Computing. Available at: https://www.cqt.sg/highlight/2025-11-nqo-quantinuum-strategic-partnership/
212. RSIS (2025) Can ASEAN Secure a Quantum Future? Available at: https://rsis.edu.sg/rsis-publication/rsis/can-asean-secure-a-quantum-future/
213. PostQuantum (2024) Quantum Technology Initiatives in Singapore and ASEAN. Available at: https://postquantum.com/quantum-computing/quantum-singapore-asean/
214. The Quantum Insider (2025) MIMOS and SDT Collaborate to Establish Malaysia's First Quantum Computing R&D Center. Available at: https://thequantuminsider.com/2025/02/25/mimos-and-sdt-collaborate-to-establish-malaysias-first-quantum-computing-rd-center/
215. Sagun Trajano, K. (2025) Can ASEAN Secure a Quantum Future? Available at: https://rsis.edu.sg/rsis-publication/rsis/can-asean-secure-a-quantum-future/
216. World Economic Forum (2025) How Saudi Arabia is moving towards a quantum economy. Available at: https://www.weforum.org/stories/2025/01/how-saudi-arabia-is-moving-towards-a-quantum-economy/
217. Ken Research (2024) KSA Quantum Computing Market Outlook to 2030. Available at: https://www.kenresearch.com/industry-reports/ksa-quantum-computing-market
218. Lucintel (2025) Quantum Computing Market in Saudi Arabia. Available at: https://www.lucintel.com/quantum-computing-market-in-saudi-arabia.aspx
219. Reuters (2024) French startup Pasqal to deploy first quantum computer in Saudi Arabia. Available at: https://www.reuters.com/technology/french-startup-pasqal-deploy-first-quantum-computer-saudi-arabia-2024-05-20/
220. Government of Saudi Arabia (2025) Aramco signs agreement to deploy first quantum computer in the Kingdom. Available at: https://my.gov.sa/en/news/1199329
221. Technology Innovation Institute (TII) (2021) TII to Build UAE's First Quantum Computer. Available at: https://www.tii.ae/news/tii-build-uaes-first-quantum-computer
222. EE Times Europe (2021) UAE to Get its First Quantum Computer and Cryptography Library. Available at: https://www.eetimes.eu/uae-to-get-its-first-quantum-computer-and-cryptography-library/
223. ATRC (2023) Technology Innovation Institute Unveils World's First Open-Source Software Library for Cryptographic Hardness Estimation. Available at: https://www.atrc.gov.ae/news/technology-innovation-institute-unveils-worlds-first-open-source-software-library
224. Mohamed bin Zayed University of Artificial Intelligence (MBZUAI) (2025) MBZUAI. Available at: https://mbzuai.ac.ae/

225. Swissnex (2025) Switzerland: A Hub for Quantum – October 2025 update. Available at: https://swissnex.org/app/uploads/2025/10/Switzerland_Hub_Quantum_Oct2025_web.pdf
226. Tageblatt (2024) Suiza inaugura su primera computadora cuántica comercial. Available at: https://tageblatt.com.ar/suiza-inaugura-su-primera-computadora-cuantica-comercial/
227. MarketScreener (2023) IonQ and QuantumBasel Partner to Achieve Future Quantum Advantages With Deployment of Two Generations of IonQ Quantum Systems in Europe. Available at: https://www.marketscreener.com/quote/stock/IONQ-INC-117182090/news/IonQ-and-QuantumBasel-Partner-to-Achieve-Future-Quantum-Advantages-With-Deployment-of-Two-Generation-44169105/
228. Swiss Federal Office for Education, Research and Innovation (SBFI) (2025) Swiss Quantum Initiative. Available at: https://www.sbfi.admin.ch/en/swiss-quantum-initiative-en
229. Ni, N. & Zhu, Y. (2023) Enabling zero knowledge proof by accelerating zk-SNARK kernels on GPU. Journal of Parallel and Distributed Computing, 173, 20–31. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0743731522002246
230. Matter Labs (2023) Introducing the ZK Stack: Your framework for building modular, sovereign, ZK Chains. Available at: https://blog.matter-labs.io/introducing-the-zk-stack-c24240c2532a
231. The Block (2023) zkSync launches new proof system called Boojum for Era mainnet. Available at: https://www.theblock.co/post/239880/zksync-launches-new-proof-system-called-boojum-for-era-mainnet
232. CoinGeek (2025) Modular ASIC-GPU Hybrids: ZK Proofs in Bitcoin mining. Available at: https://coingeek.com/modular-asic-gpu-hybrids-zk-proofs-in-bitcoin-mining/
233. Khan, A. A., Laghari, A., Almansour, H., Jamel, L., Hajjej, F., Estrela, V. V., Mohamed, M. A. & Ullah, S. (2025) Quantum computing empowering blockchain technology with post-quantum resistant cryptography for multimedia data privacy preservation in cloud-enabled public auditing platforms. Journal of Cloud Computing: Advances, Systems and Applications, 14(1), 1-16. Available at: https://link.springer.com/article/10.1186/s13677-025-00771-8
234. AIP (2024) Survey on the Potential Impact of Quantum Computing. Available at: https://pubs.aip.org/aip/acp/article/3263/1/030006/3359154
235. INSPIRE-HEP (2025) Practical Iterative Quantum Consensus Protocol With Sharding Construction. Available at: https://inspirehep.net/literature/3064105
236. Yang, Z., Alfauri, H., Farkiani, B., Jain, R., Di Pietro, R. & Erbad, A. (2024) A Survey and Comparison of Post-quantum and Quantum Blockchains. IEEE Communications Surveys & Tutorials, 26(2), 967–1002. Available at: https://arxiv.org/pdf/2409.01358
237. Reddy, N. R. et al. (2025) QuantumShield-BC: Quantum secured blockchain framework for enhancing post-quantum data security. Scientific Reports. Available at: https://www.nature.com/articles/s41598-025-16315-8
238. Reuters (2025) Europol body: Banks should prepare for quantum computer risk now. Available at: https://www.reuters.com/technology/cybersecurity/europol-body-banks-should-prepare-quantum-computer-risk-now-2025-02-07/
239. U.S. Congress (2022) Quantum Computing Cybersecurity Preparedness Act (H.R. 7535). Available at: https://www.congress.gov/bill/117th-congress/house-bill/7535
240. European Commission (2024) Commission publishes Recommendation on Post-Quantum Cryptography. Available at: https://digital-strategy.ec.europa.eu/en/news/commission-publishes-recommendation-post-quantum-cryptography
241. The Guardian (2025) UK cybersecurity agency warns over risk of quantum hackers. Available at: https://www.theguardian.com/technology/2025/mar/20/uk-cybersecurity-agency-quantum-hackers
242. Reuters (2025) Europol body: Banks should prepare for quantum computer risk now. Available at: https://www.reuters.com/technology/cybersecurity/europol-body-banks-should-prepare-quantum-computer-risk-now-2025-02-07
243. Barron's (2025) Cloudflare is bulking up to fight the quantum attack. Available at: https://www.barrons.com/articles/cloudflare-quantum-computers-cybersecurity-7e41dbaa
244. PR Newswire (2025) BTQ Technologies Unveils Quantum Stablecoin Settlement Network (QSSN) Available at: https://www.prnewswire.com/news-releases/btq-technologies-unveils-quantum-stablecoin-settlement-network-qssn-302489583.html
245. Boston Consulting Group (2024) Quantum Computing On Track to Create Up to $850 Billion of Economic Value By 2040. Available at: https://www.bcg.com/press/18july2024-quantum-computing-create-up-to-850-billion-of-economic-value-2040
246. McKinsey (2025) The Year of Quantum: From Concept to Reality in 2025. Available at: https://www.mckinsey.com/capabilities/tech-and-ai/our-insights/the-year-of-quantum-from-concept-to-reality-in-2025
247. The Quantum Insider (2025) Top Quantum Computing Companies. Available at: https://thequantuminsider.com/2025/09/23/top-quantum-computing-companies/

248. SpinQ (2025) Quantum Computing Industry Trends 2025: A Year of Breakthrough Milestones and Commercial Transition. Available at: https://www.spinquanta.com/news-detail/quantum-computing-industry-trends-2025-breakthrough-milestones-commercial-transition
249. SpinQ (2025) Quantum Computing Industry Trends 2025: A Year of Breakthrough Milestones and Commercial Transition. Available at: https://www.spinquanta.com/news-detail/quantum-computing-industry-trends-2025-breakthrough-milestones-commercial-transition
250. Google Research (2024) Making quantum error correction work. Available at: https://research.google/blog/making-quantum-error-correction-work/
251. IBM Quantum (2025) How IBM will build the world's first large-scale, fault-tolerant quantum computer. Available at: https://www.ibm.com/quantum/blog/large-scale-ftqc
252. NVIDIA (2025) "Quantum Computing." Available at: https://www.NVIDIA.com/en-gb/high-performance-computing/
253. Xanadu (2025) Xanadu unveils first on-chip error-resistant photonic qubit. Available at: https://www.xanadu.ai/press/xanadu-unveils-first-on-chip-error-resistant-photonic-qubit/
254. IBM (2025) IBM Quantum hardware and roadmap — Hardware for useful quantum computing. Available at: https://www.ibm.com/quantum/hardware
255. Microsoft (2025) Quantum Error Correction. Available at: https://quantum.microsoft.com//en-us/insights/education/concepts/quantum-error-correction
256. NVIDIA (2025) CUDA Quantum. Available at: https://developer.NVIDIA.com/cuda-quantum
257. Hirvonen, A., Savolainen, J. & Snellman, H. (2025) Quantum computing is coming – Is the financial sector ready? Bank of Finland Bulletin. Available at: https://www.bofbulletin.fi/en/2025/articles/quantum-computing-is-coming-is-the-financial-sector-ready/
258. PQShield (2025) The BIS publishes quantum-readiness roadmap for the financial system. Available at: https://pqshield.com/the-bis-publishes-quantum-readiness-roadmap-for-the-financial-system/; FutureMarketInsights (2025) Post-Quantum Cryptography (PQC) Migration Market. Available at: https://www.futuremarketinsights.com/reports/post-quantum-cryptography-pqc-migration-market