The Industrial State of Quantum Computing: A Realist's Assessment (2023-2025)

Report Date: November 8, 2025
Coverage Window: November 2023 – November 2025, with selective pre-2023 context for roadmap and definitional clarity.

1. Introduction: Navigating a Maturing Ecosystem

The period from late 2023 to late 2025 has marked a pivotal transition for quantum computing, moving it decisively from a purely research-oriented field to one undergoing rigorous industrial validation. The era of Noisy Intermediate-Scale Quantum (NISQ) devices—systems with tens to thousands of qubits that are not yet fault-tolerant—is being superseded by the first tangible demonstrations of error-corrected logic. This shift necessitates a new framework for evaluation, one that prioritizes reproducible, task-oriented performance over raw physical specifications.

This report is structured for professionals who are knowledgeable in quantum computing but may not be experts across every technological modality or benchmark. It aims to provide a clear-eyed assessment of progress, grounded in verifiable evidence and comparable metrics. The central thesis is that the industry's center of gravity has moved beyond qubit counts to a more sophisticated conversation about error correction, system integration, and practical utility.

How to Read This Report

- **Evidence Bar:** Claims regarding Quantum Error Correction (QEC)—the process of encoding quantum information across multiple physical qubits to detect and correct errors—and logical qubits (the error-protected information units resulting from QEC) are supported by A/B-grade artifacts. These are peer-reviewed papers or detailed preprints that include comprehensive methods, datasets, descriptions of syndrome extraction (the process of measuring errors), decoder behaviour (the algorithms that interpret and correct errors), and clear error margins, enabling independent verification.
- **Comparable Metrics:** To enable fair comparisons across different technological approaches, this report consistently uses a standardized set of metrics:
    - **Physical vs. Logical Qubits:** Distinguishing between the raw, error-prone hardware components and the stable, error-corrected information units.

- **Two-Qubit Gate Fidelity:** The probability that a fundamental entangling operation executes correctly, a critical bottleneck for complex algorithms.
- **T1/T2 Coherence Times:** T1 (energy relaxation time) measures how long an excited qubit retains its energy; T2 (dephasing time) measures how long a qubit maintains its quantum phase coherence. Both limit the duration of computations.
- **Code Distance (d):** A measure of an error-correcting code's robustness, indicating how many errors it can correct.
- **Quantum Volume (QV):** A composite metric that attempts to capture overall computational power by considering qubit number, fidelity, and connectivity.
- **Throughput:** The rate at which quantum circuits can be executed while maintaining a target fidelity.

- **Scope Boundaries:** It is crucial to distinguish between different quantum technologies:
  - **Quantum Key Distribution (QKD)** is a technology for secure communications and is not a metric for computational reliability.
  - **Annealing** (specifically, adiabatic quantum optimization for Ising models) is a specialized approach for combinatorial optimization and is distinct from the universal gate-model quantum computing that underpins most algorithm development. Progress in QKD or annealing should not be conflated with progress toward fault-tolerant, gate-based quantum computing.
- **Benchmarks:** Where available, results are contextualized within task-grounded frameworks like the U.S. Defense Advanced Research Projects Agency (DARPA) Quantum Benchmarking Initiative (QBI), which emphasizes falsifiable, utility-oriented measurements over peak device performance.

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2. Executive Summary: From Concept to Operational Reality

The last two years have witnessed the industry surpassing a critical psychological and technical threshold: the demonstration of logical qubits with repeated QEC cycles where the logical error rate per cycle falls below the uncorrected physical error rate. This "below break-even" milestone, most rigorously demonstrated on trapped-ion platforms, represents the minimal technical condition for building towards meaningful fault-tolerant quantum computation. It proves that adding more qubits for error correction can indeed improve computational integrity, a foundational principle that had previously been only theoretical.

Beyond this core advance, the ecosystem has matured along several parallel tracks:

- **Superconducting circuits** have progressed through documented processor families and the strategic deployment of the first IBM Quantum System Two outside the United States at the RIKEN research institute in Kobe, Japan. This installation embodies the concept of "quantum-centric supercomputing," where a Quantum Processing Unit (QPU) is integrated with classical High-

Performance Computing (HPC) resources, enabling end-to-end workflow testing with real-time telemetry on practical problems in chemistry and optimization.
- **Neutral-atom arrays** have entered the scaling phase, with vendors publicly disclosing systems of over 1,000 atoms. Their technical documentation now provides the necessary detail on Rydberg-mediated entangling gates and calibration automation, allowing for realistic pilot project scoping for many-body simulation and optimization tasks.
- **Photonics** has achieved a significant manufacturing milestone with a demonstrable, 300-mm silicon-photonics platform for Measurement-Based Quantum Computing (MBQC). The focus is now shifting from individual components to subsystem integration, with a clear engineering agenda centered on managing aggregate optical loss (measured in decibels, dB) and end-to-end fidelity.
- **Annealing** continues to serve as a specialized, non-universal tool for combinatorial optimization within hybrid solvers. Its evaluation requires a distinct evidence standard, reliant on complete problem instances, embedding strategies, and direct comparisons to tuned classical algorithms.

Across all modalities, government initiatives like DARPA's QBI are steering the community toward reproducible, task-grounded results. For potential adopters, the guidance is clear: prioritize environments that provide transparent telemetry, hybrid workflow support, and comprehensive error budgets over those that simply advertise high qubit counts.

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3. Market Landscape: The Four-Modality Stack and Specialized Tracks

The commercial quantum computing market has crystallized around a core stack of four competing and complementary modalities: superconducting circuits, trapped ions, neutral atoms, and photonics. Alongside this stack exists annealing as a specialized optimization track. Each modality now has a mature enough ecosystem to allow for reasonable comparison based on primary vendor documentation and peer-reviewed literature.

The most significant market signal is the operationalization of integrated systems. The IBM-RIKEN Quantum System Two deployment in Kobe is a concrete example of "quantum-centric supercomputing" moving out of the lab. This model, which involves co-designing quantum and classical workflows at the level of job scheduling, circuit compilation, and runtime telemetry, provides the necessary infrastructure to assess real-world application performance.

The evidence posture for each modality has also become more defined:

- **Trapped-ion** platforms currently provide the most rigorous, A-grade evidence for below-break-even QEC, with publications that allow for full independent scrutiny of their methods and data.
- **Superconducting** advances are documented through a mix of platform documentation (B-grade) and deployment reports, with the highest-profile scale markers (e.g., the 1,121-qubit Condor processor) serving as reference points for engineering progress.
- **Neutral-atom** vendors have made their control stacks publicly legible (B/C-grade), enabling realistic pilot scoping based on array size, gate fidelity, and calibration stability rather than speculative potential.
- **Photonics** has established a credible device-level integration pathway (A-grade from a high-impact journal), with a clear roadmap for the next stage of subsystem development.
- **Annealing** continues to attract enterprise pilots in finance and logistics, but its credibility is entirely dependent on the provision of complete problem artifacts for comparison.

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4. Technology Deep-Dive: Architectural Progress and Hurdles

4.1 Superconducting Circuits

Superconducting qubits are implemented as engineered microwave resonators (transmons) that operate at millikelvin temperatures within dilution refrigerators to suppress thermal noise. The engineering focus for this modality is intensely practical: improving two-qubit gate fidelity, managing crosstalk via tunable couplers and specialized layouts (like IBM's heavy-hex connectivity), maintaining calibration stability, and developing compilers that are aware of hardware connectivity and error profiles.

IBM's public processor documentation provides unprecedented insight into the performance and limitations of these systems. The Kobe deployment is the critical testbed for evaluating how these devices function within a larger computational workflow. Here, the QPU and an HPC cluster cooperate on problems in chemistry and materials science, with end-to-end telemetry providing data on queue times, calibration drift, and the real-world effectiveness of error mitigation. While roadmap markers like the 1,121-qubit Condor processor demonstrate scaling capability, operational users are increasingly focused on how fidelity, coherence times, and intelligent software combine to support reliable "circuit depth" for their specific workloads.

4.2 Trapped Ions

Trapped-ion platforms confine atomic ions using electromagnetic fields and use lasers or microwaves to perform quantum gates. Their inherent strengths include long coherence times and high gate fidelities, which have made them the leading modality for early, rigorous QEC demonstrations.

The landmark achievement in this period has been the publication of results demonstrating 12 logical qubits undergoing repeated QEC cycles, including the entanglement of four logical qubits in a nonlocal code. Crucially, these papers include full details on syndrome extraction, decoder algorithms, and error bars. This transparency allows third parties to verify the central claim: that the logical error per cycle is indeed lower than the uncorrected physical error per cycle. These results have moved QEC from a theoretical promise to an experimentally validated phenomenon, establishing a concrete benchmark for what "below break-even" operation means in practice, including how the speed of error detection and correction (syndrome cadence and decoder latency) impacts the overall suppression of errors.

4.3 Neutral Atoms

Neutral-atom systems use arrays of optical tweezers to trap individual atoms in reconfigurable lattices. Entangling gates are performed by exciting atoms to high-energy Rydberg states, which allows them to interact strongly over micrometer-scale distances. Public disclosures from vendors now detail systems with ~1,000 or more atoms, along with specifications on addressing precision, automated calibration pipelines, and Rydberg gate parameters.

This modality's architecture emphasizes "width" over "depth"—they can execute many gates in parallel across a large array but are currently limited in the number of sequential operations they can perform. For potential users, the key question is how this parallelism, combined with compilation strategies and stable calibration, delivers consistent accuracy and throughput for specific problem classes, such as simulating quantum many-body systems or solving structured optimization problems. Early small-scale logical encoding experiments are underway, but the primary near-term value proposition lies in analogue quantum simulation.

4.4 Photonics

Photonic quantum computing encodes quantum information in particles of light (photons). The leading approach, Measurement-Based Quantum Computing (MBQC), works by first preparing a large, entangled "cluster state" and then performing a sequence of adaptive measurements to enact a computation. A seminal 2025 paper published in *Nature* demonstrated a manufacturable silicon-photonics platform that integrates single-photon sources, switches, and detectors on 300-mm wafers, with device-level performance data on optical loss and efficiency.

The primary challenge for photonics is now one of subsystem integration. The field has a clear agenda to construct small, functional resource states and meticulously quantify the end-to-end optical loss (in dB) and the resulting fidelity budget. Prospective users should look for peer-reviewed evidence of these integrated subsystems as the key indicator of progress toward computational utility.

4.5 Annealing

Quantum annealing is a specialized form of quantum computation designed to find low-energy solutions to optimization problems formulated as Ising models. It is not a universal gate-model system and should not be evaluated by QEC metrics. Commercial annealers are large lattices of superconducting flux qubits with programmable couplers. The system is evolved from a simple initial state to a final state that encodes the problem solution according to a specific "anneal schedule."

The performance of an annealer is exquisitely sensitive to the problem being solved. It depends entirely on the problem structure, how it is embedded onto the hardware's connectivity graph, device calibration, and the design of the anneal schedule. Therefore, any claim of a "quantum advantage" or even meaningful performance is only credible if accompanied by the complete problem instance, the embedding used, the schedule parameters, the outputs, and results from a well-tuned classical baseline solver. Without these open artifacts, performance claims are uninterpretable.

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5. Benchmarks and Metrics: Standardizing the Conversation

As the field matures, comparing progress requires a stable and consistent set of metrics. The following table summarizes the state of the four core modalities and the specialized annealing track against these standardized measures.

Modality	Physical Qubits (Max)	Logical Qubits (Demo)	Two-Qubit Fidelity (Context)	Code Distance d (Context)	Evidence Grade
Superconducting	1,121 (Condor roadmap marker)	Multi-logical entanglement in nonlocal code	99%–99.9% (system-dependent)	d≈3–5 in recent code studies	A/B/C
Trapped Ion	Dozens per device at high fidelity	**12 logical with repeated QEC**	~99.8% in leading systems	d≥5–7 reported	A
Neutral Atom	~1,000+ (AC1000 class)	Early small-logical encodings	~99.5% Rydberg gates (vendor data)	Small-d experiments underway	B/C
Photonic	100+ modes at device level	N/A (system-level in progress)	99% component-level targets	N/A	A
Annealing	Thousands of flux qubits with dense couplers (generation-dependent)	N/A (not gate-model QEC)	N/A (performance is schedule/embedding-based)	N/A (no code distance)	C

Beyond these hardware-specific metrics, operational benchmarks are becoming increasingly important. The behaviour of compilers, the efficiency of job schedulers, and the stability revealed by calibration telemetry—as seen in deployments like the Kobe system—are now essential parts of the performance conversation, as they directly determine the reliability and reproducibility of results.

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6. Commercialization Signals: From Lab Demos to Pilot-Ready Environments

The commercialization of quantum computing is now characterized by a focus on transparency, integration, and reproducible artifacts.

- **IBM--RIKEN System Two:** This installation formalizes the quantum-centric supercomputing model. By providing telemetry on queueing, calibration drift, compilation choices, and runtime reliability, it enables application-level assessments that were previously impossible. This moves the conversation from "what can the device do?" to "what can we accomplish with the entire system?"

- **Microsoft and Quantinuum:** These companies set a new standard for announcing breakthroughs by directly linking press releases to detailed arXiv preprints. This practice ties logical qubit milestones directly to the underlying experimental data, showing how QEC primitives can be integrated into cloud-based developer workflows alongside classical verification backends.
- **Neutral-Atom Providers:** By disclosing architectural and control details, these vendors have empowered potential customers to scope pilots based on achievable depth and accuracy, moving beyond vague promises of scale.
- **Annealing Deployments:** While ongoing in finance and logistics, the onus is now on vendors and users to provide full, reproducible artifacts—problem instances, embeddings, schedules, and classical baselines—to substantiate any claims of value.

Industry guidance from analyst firms and consortia increasingly emphasizes these evidence attributes as the basis for near-term procurement and pilot project selection.

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7. Risk and Hype Assessment: A Disciplined Approach to Evaluation

In a rapidly advancing field, a disciplined approach to separating validated progress from marketing hype is essential. The following framework is recommended:

- **Insist on A/B-Grade Artifacts:** For any claim related to computing reliability, especially QEC, the acceptance bar must be a peer-reviewed or detailed preprint with full methods, datasets, syndrome extraction details, decoder descriptions, and error bars. This allows for third-party replication.
- **Maintain Conceptual Separation:** Do not conflate QKD (a communications security technology) with QEC (a computing reliability technology). They are orthogonal domains.
- **Look Beyond Qubit Counts:** A high physical qubit count is meaningless without corresponding data on two-qubit fidelity, T1/T2 coherence times, crosstalk, decoder performance, and compiler efficiency.
- **Demand Task-Grounded Benchmarks:** Prefer benchmarks that run complete, meaningful tasks and are directly compared against state-of-the-art classical solvers, with all telemetry available.

Confidence levels vary significantly by modality:

- **High Confidence:** For trapped-ion QEC milestones backed by complete methods and data.
- **Moderate Confidence:** For superconducting advances reliant on platform documentation, unless accompanied by A/B-grade preprints.
- **Emerging Confidence:** For neutral-atom scaling, pending independent third-party replications of vendor claims.
- **Specialized Confidence:** For annealing, which is only meaningful when evaluated with fully open problem instances and baselines.

Programs like DARPA's QBI are actively improving the signal-to-noise ratio by tying funding and selection to these falsifiable, evidence-based standards.

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8. Timeline of Key Developments (November 2023 – November 2025)

- **IBM's Condor Roadmap Marker:** The announcement of the 1,121-qubit Condor processor set a clear benchmark for scale in the superconducting modality, simultaneously highlighting the engineering challenge of translating raw qubit count into application-relevant computational depth under real-world error constraints.
- **Trapped-Ion QEC Breakthroughs:** Multiple teams published results demonstrating repeated QEC on 12 logical qubits and the entanglement of four logical qubits. The provision of full methods and datasets set a new standard for evidence, allowing the community to independently verify below-break-even operation.
- **Neutral-Atom Scaling Disclosure:** Vendors publicly released product and technical materials detailing ~1,000+ atom arrays, including specifications on addressing, calibration, and Rydberg gate parameters. This transparency enables realistic pilot project scoping for the first time.
- **Photonic Manufacturing Milestone:** The publication of a manufacturable, 300-mm silicon-photonics platform in *Nature* provided a credible, scalable hardware pathway for MBQC, shifting the focus to subsystem integration and loss management.
- **IBM-RIKEN System Two Deployment:** The installation of the first IBM Quantum System Two outside the U.S. in Kobe, Japan, created the first open, operational environment for testing quantum-centric supercomputing workflows with reproducible telemetry alongside HPC resources.

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9. Forecast: The Next 12–24 Months

Based on current trajectories, the following developments are likely, with clear criteria for success and failure:

- **Trapped-Ion Scaling to 20-50 Logical Qubits:** This is likely if subsequent papers show sustained logical error suppression with improved syndrome measurement speed and decoder efficiency. It will be falsified by an absence of new A/B-grade artifacts or a regression in error suppression.
- **Neutral-Atom End-to-End Pilots:** Likely if providers publish full execution traces, accuracy data versus classical baselines, and fidelity-aware throughput metrics for their ~1,000-atom arrays. It will be falsified by anecdotal success claims without published input and output data.
- **Photonic Subsystem Integration:** Likely if peer-reviewed papers emerge that quantify the end-to-end loss (in dB) and fidelity of integrated MBQC

subsystems. It will be falsified by updates that focus solely on improved individual components without demonstrating functional integration.

- **Quantum-Centric Case Studies from Kobe:** Likely if public reports from the RIKEN deployment provide detailed data on schedulers, compiler performance, error-mitigation settings, and runtime reliability, with sufficient information for third-party reproduction. It will be falsified by high-level marketing narratives lacking technical depth.
- **Annealing Hybrid Benchmarks with Open Artifacts:** Likely if the community or vendors adopt standardized benchmarking suites that mandate the release of full problem instances, embeddings, schedules, outputs, and classical baselines. It will be falsified by performance reports that rely on qubit counts or proprietary data.

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10. Implications for Adopters: A Strategic Guide

For organizations considering near-term quantum computing pilots, a strategic and evidence-based approach is critical.

1. **Prioritize Transparent Environments:** Choose providers and platforms that offer A/B-grade artifacts for their core claims, especially regarding QEC. The environment should provide comprehensive telemetry on system performance, including job queueing, calibration drift, compiled circuit depth, and the impact of error-mitigation techniques.
2. **Demand Task-Grounded Baselines:** Insist on seeing performance compared against state-of-the-art classical solvers on complete, well-defined tasks. This is the only way to assess whether a quantum approach offers any tangible benefit.
3. **Treat QKD as Orthogonal:** Understand that QKD is a technology for securing communication channels. It is unrelated to the maturity or capability of gate-based quantum computers.
4. **Evaluate Annealing Rigorously:** When assessing quantum annealing, ignore qubit counts. Instead, scrutinize the problem embedding onto the hardware, the anneal schedule parameters, and, most importantly, the performance against powerful classical optimization algorithms. Verify that the problem structure is a good match for the device's specific connectivity and control capabilities.

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11. Glossary

- **NISQ:** Noisy Intermediate-Scale Quantum. Refers to the current generation of quantum processors that have a non-trivial number of qubits but are not yet fault-tolerant.

- **QEC:** Quantum Error Correction. A set of techniques to protect quantum information from errors by encoding it across multiple physical qubits.
- **Logical Qubit:** A fault-tolerant qubit encoded using QEC, composed of multiple physical qubits.
- **QKD:** Quantum Key Distribution. A secure communication method that uses quantum mechanics to encrypt and exchange keys.
- **QPU:** Quantum Processing Unit. The hardware component that performs quantum computations.
- **HPC:** High-Performance Computing. The use of powerful supercomputers and parallel processing techniques to solve complex computational problems.
- **T1:** Energy Relaxation Time. The time constant for a qubit to decay from its excited state to its ground state.
- **T2:** Dephasing Time. The time constant for a qubit to lose its phase coherence.
- **QV:** Quantum Volume. A single-number metric that aims to capture the overall performance and capability of a quantum computer.
- **MBQC:** Measurement-Based Quantum Computing. A model of quantum computation where computation is carried out by performing a sequence of measurements on an initially prepared entangled state (a cluster state).
- **d:** Code Distance. In QEC, a measure of the error-correcting code's power, indicating the number of errors it can detect and correct.
- **Annealing:** In this context, adiabatic quantum optimization, a specialized approach for solving combinatorial optimization problems.

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