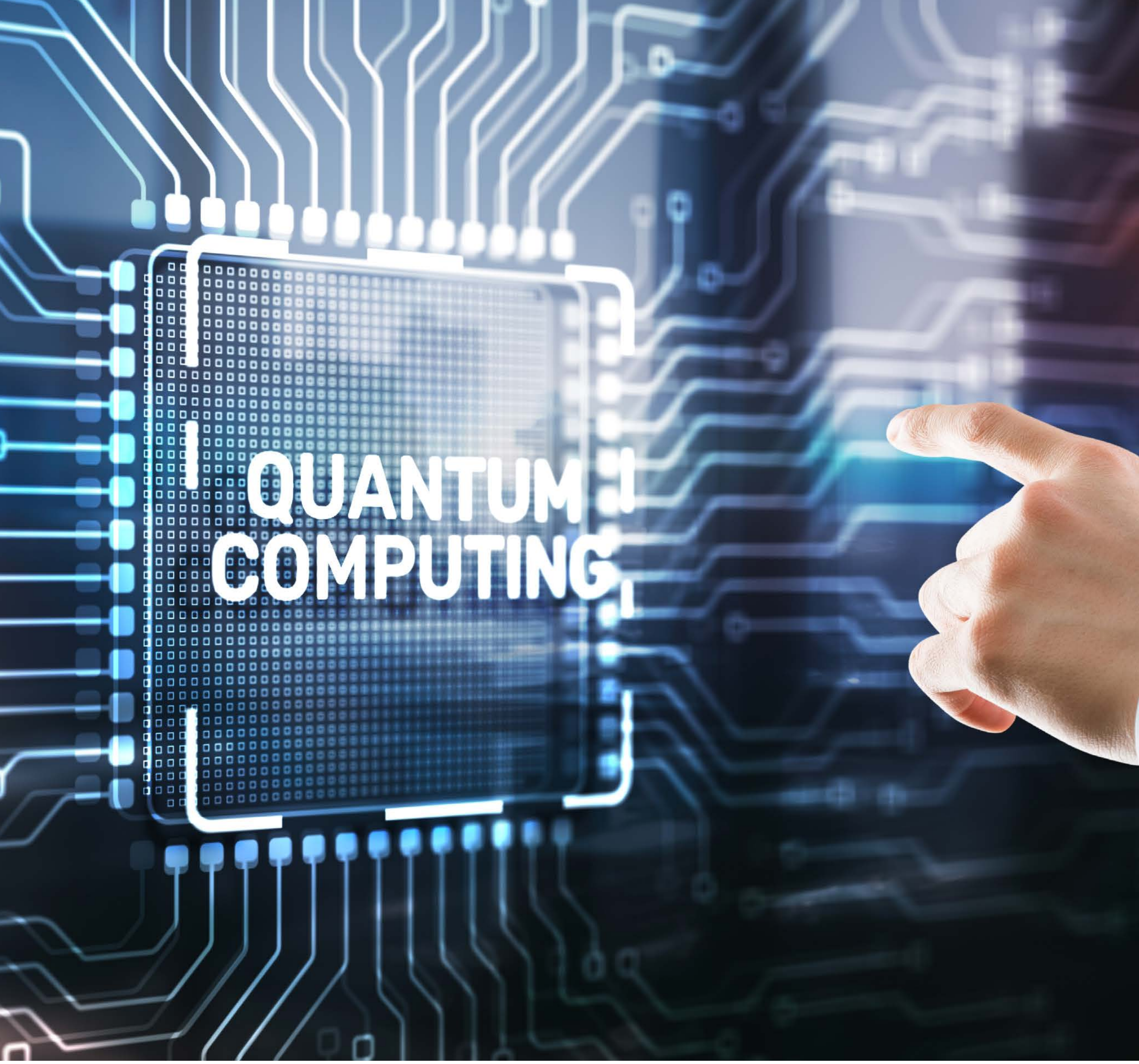

JUNE, 2024

U.S. Quantum Technology Leadership Hinges on Federal Policy in the 118th Congress

ALLISON SCHWARTZ

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EXECUTIVE SUMMARY

Quantum computing, a technology that uses quantum mechanics to perform computation at speeds greater than today's "classical" computers, has the power to revolutionize private and public sector problem-solving. Pressing real-world challenges such as electrical grid resilience, port optimization, global supply-chain management, emergency management and response, infrastructure development, sustainability, and the security of telecommunication networks can all be addressed by quantum applications.

This policy report examines the current state of the quantum industry, including rapid advancements that have occurred over the past five years. Two quantum computing "modalities" will be distinguished: annealing, which is being used to solve optimization problems today, and gate-model, where the applications are mostly further off in the future. Most problems will continue to need classical computations for parts of those problems, therefore, quantum-classical hybrid applications — where quantum computing technologies work synergistically with classical computers — are being developed to solve challenging problems.

From the policy perspective, understanding the different quantum computing technologies is important because Congress is in the process of reauthorizing and expanding the National Quantum Initiative (NQI) Act[1] which expired on September 30, 2023. In addition, a variety of other quantum-related initiatives are being considered by Congress.

Up to now, the federal government has mostly focused on supporting longer-term basic research in quantum technology, which is important for long-term competitiveness. But the government also has an important role to play in supporting near-term quantum technologies such as annealing.

This paper offers policy recommendations for the reauthorization and expansion of the NQI and related legislation, including:

- Boosting investment in long-term hardware advancements to keep up with other countries.
- Ensuring that the NQI addresses the full range of near-term and long-term technologies, including regularly conducting technology readiness-level (TRL) assessments.
- Supporting the development and deployment of near-term use cases through new quantum sandbox programs.

1. *Quantum.gov, an official website of the U.S. government, www.quantum.gov*

- Enhancing access to commercial quantum systems by funding the quantum user access program (QUEST) authorized in the CHIPS and Science Act.[2]
- Building an integrated high-performance computing and quantum computing data-center domestic infrastructure.
- Supporting domestic component and chip fabrication in addition to commercial-scale rapid prototyping research and development.
- Enhancing international quantum cooperation agreements to include commercialization, talent development, and supply chains as well as academic research.

In addition, the NQI and related legislation must support the development of a skilled workforce that can support the growing U.S. quantum industry, and the end users of the technology both in the private and public sectors. That means funding talent programs that permit students to access the variety of quantum computing training courses created by industry, and supporting academic programs that attract and retain talent from diverse and underserved populations.

INTRODUCTION

In the world of technology, five years is a lifetime. Every major technological advancement opens the door to countless opportunities to innovate. These innovations compound and build rapidly, rendering once disruptive technology commonplace.

While technology advances at a lightning-quick pace, the nature of government is slower and more deliberate. As a result, government often plays catch up with deploying today's technology.

This challenge is evident with the progression of U.S. quantum policy. To date, U.S. policy has not kept up with the quick evolution of the quantum industry. Other countries are already realizing the benefits of quantum technological advancements and recognizing that such technology can be a game changer for solving pressing public sector problems.

BACKGROUND: THE STATE OF TODAY'S QUANTUM INDUSTRY

Broadly, quantum computing applies quantum-mechanical effects like superposition, entanglement, and tunneling to solve computationally hard problems potentially faster than purely classical computing.[3] Quantum computers are comprised of quantum bits, or qubits, which are quantum computing's version of bits, classical computing's most basic form of information. Qubits are fundamentally different and much more powerful than bits.[4] Qubits can be made from different materials and architectures including superconducting, ion traps, photonics, neutral atoms, and more.

Within quantum computing, there are two primary approaches: *annealing and gate-model.* Annealing quantum computing, which is considered a near-term technology, is commercial-grade and market-ready. Quantum annealing is best for optimization challenges

2. *117th Congress, "CHIPS and Science Act," H.R. 4346 (Public Law 117-167), August 9, 2022, https://www.congress.gov/bill/117th-congress/house-bill/4346.*
3. *Andrew D. King et al, "Quantum Critical Dynamics in a 5,000-qubit Programmable Spin Glass," Nature, April 19, 2023 https://www.nature.com/articles/s41586-023-05867-2.*
4. *Shannon Brescher Shea, "Creating the Heart of a Quantum Computer: Developing Qubits," Department of Energy, Office of Science, February 10, 2020, https://www.energy.gov/science/articles/creating-heart-quantum-computer-developing-qubits.*

and is uniquely suited to solving problems like electrical grid resilience, supply chain management, and logistics challenges.

Gate-based quantum technologies are expected to be better suited for other problem sets including material design and personalized medicine. While some gate-based systems are available today, currently, they fall into what's known as the "Noisy Intermediate Scale Quantum (NISQ)" classification. These systems, while potentially very powerful, are prone to considerable error rates, and limited in size by the number of logical qubits. That currently makes them unreliable to perform general computation.[5]

In addition, "quantum-classical hybrid" refers to a class of algorithms that combine both quantum and classical systems.[6] Hybrid applications provide faster analysis and more optimal solutions for problems involving a large number of variables, such as weather fluctuations, potential national security threats, or scheduling thousands of employees across hundreds of locations.

A SHORT SUMMARY OF QUANTUM MECHANICS & QUANTUM SYSTEMS

Superposition is a quantum mechanical concept whereby a system can exist in multiple different states, e.g. a qubit can exist as a 0 and a 1, or both or neither simultaneously; Entanglement is when two or more quantum particles become state-dependent on each other; Tunneling is when particles probabilistically may pass through a barrier that classical physics would prohibit.

ANNEALING QUANTUM COMPUTING

Quantum annealing simply uses quantum physics to find low-energy states of a problem and, therefore, the optimal or near-optimal combination of elements. Quantum annealing has the potential to change the way businesses and governments operate by helping cut costs, saving time, driving revenue growth, and accelerating innovation. In fact, International Data Corporation (IDC) identified quantum annealing as a core quantum system in its 2023 Worldwide Quantum Computing Taxonomy.[7] Annealing quantum computing is best for optimization, which is more than efficiency, it is the ability to arrive at optimal decisions that fully account for multiple layers of constraints and ever-increasing amounts of data.[8] Research from Cornell University outlines the clear advantages of quantum annealing over gate-model for solving optimization problems.[9]

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5. *James Dargan, "What is Quantum Computing," The Quantum Insider, March 13, 2023, https://thequantuminsider.com/2023/03/13/what-is-nisq-quantum-computing/.*
6. *Dr. Chetan Nayak, "Full Stack Ahead: Pioneering Quantum Hardware Allows For Controlling Up To Thousands Of Qubits At Cryogenic Temperatures," Microsoft Research Blog, January 27, 2021, https://www.microsoft.com/en-us/research/blog/full-stack-ahead-pioneering-quantum-hardware-allows-for-controlling-up-to-thousands-of-qubits-at-cryogenic-temperatures/.*
7. *Heather West et al, "IDC's Worldwide Quantum Computing Taxonomy, 2023," International Data Corporation (IDC), May 2023, https://www.idc.com/getdoc.jsp?containerId=US49198723.*
8. *Alan Baratz, "The Role Of Today's Quantum Technology In Fueling A Future-Proof Business," Forbes, June 26, 2023, https://www.forbes.com/sites/forbestechcouncil/2023/06/26/the-role-of-todays-quantum-technology-in-fueling-a-future-proof-business/?sh=5522cc34384e.*
9. *Ryan Babbush et al, "Compilation of Fault-Tolerant Quantum Heuristics for Combinatorial Optimization," Cornell University, July 14, 2020, https://arxiv.org/abs/2007.07391.*

GATE-MODEL QUANTUM COMPUTING

Gate-model systems available today are called noisy intermediate scale quantum (NISQ) computing, a term coined by John Preskill in 2018.[10] These systems are more impacted by "noise," which refers to multiple factors that can affect the accuracy of quantum computer calculations.[11] This fragility renders gate-model systems further from tackling today's real-world problems. However, these systems are important because, once developed, they will likely be better at solving a different set of problems such as materials science and personalized medicines. Continued investment in gate-model hardware is focused on obtaining breakthroughs in chip design and qubit coherence, the length of time where a qubit retains its information, which is important for tackling larger problems sets.

According to an IDC Spotlight paper,

> *"Gaining Near-Term Advantage Using Quantum Annealing," Doc#S51050523, July 2023, "Currently, these highly anticipated gate-based systems are unable to provide large-scale or near-term advantage.*
>
> *Comparatively, quantum annealing offers an approach for enterprises seeking to gain a quantum advantage when solving optimization problems."*[12]

QUANTUM-CLASSICAL HYBRID

In quantum-classical hybrid approaches, a hybrid solver will break down the problem into parts, some of which are best suited for classical systems, as some problems have components suited for classical computation, and other parts of the problem are best solved by the quantum processing unit (quantum annealing or gate-model).

Support for hybrid approaches is growing. The Hudson Institute's Quantum Alliance Initiative released a report stating that "the true path to the quantum future is the combination of quantum and classical digital technology, especially in computing, which will powerfully accelerate access to the potential benefits of quantum information science."[13] Terra Quantum, a European-based company, argues that hybrid will drive the industry toward increasing adoption of quantum computing.[14]

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10. *John Preskill, "Quantum Computing in the NISQ era and beyond," Cornell University, July 31, 2018, https://arxiv.org/abs/1801.00862.*
11. *Juan Moreno et al, "Noise in Quantum Computing," AWS Quantum Technologies Blog, September 8, 2022, https://aws.amazon.com/blogs/quantum-computing/noise-in-quantum-computing/#:~:text=Noise%20refers%20to%20the%20multiple,calculations%20a%20quantum%20computer%20performs*
12. *IDC Spotlight, sponsored by D-Wave Quantum, "Gaining Near-Term Advantage Using Quantum Annealing," Doc #S51050523, July 2023, https://www.dwavesys.com/media/3rkmzagg/idc-spotlightf.pdf.*
13. *Arthur Herman, "Advancing the Quantum Advantage: Hybrid Quantum Systems and the Future of American High-Tech Leadership," Hudson Institute Quantum Alliance Initiative, November 2022, https://s3.amazonaws.com/media.hudson.org/Advancing+the+Quantum+Advantage+Hybrid+Quantum+Systems+and+the+Future+of+American+High-Tech+Leadership.pdf.*
14. *Markus Pflitsch and Karan Pinto, "The Future is Hybrid: How hybrid can accelerate the early industrial application of quantum computing," TechUK, https://www.techuk.org/resource/the-future-is-hybrid-how-hybrid-can-accelerate-the-early-industrial-application-of-quantum-computing.html.*

EXAMPLES OF CURRENT QUANTUM COMPANIES AND APPLICATIONS

Table 1 shows some of the top quantum computing companies that are driving this cutting-edge technology forward.[15]

TABLE 1: SOME LEADERS IN QUANTUM COMPUTING

1	IBM. (U.S.)
2	Google Quantum AI (U.S.)
3	Amazon (U.S.)
4	Microsoft. (U.S.)
5	Intel. (U.S.)
6	D-Wave (U.S./CA)
7	Quantinuum (U.K./U.S.)
8	Rigetti (U.S.)
9	Xanadu (CA)
10	Atos Computing (FR)

Note: Alibaba and Baidu recently announced plans to quit quantum computing research and move their projects to universities.

Many companies have built quantum applications for a variety of different uses, mainly using annealing and hybrid technologies. For example:

- POLARISqb, a North Carolina-based company, accelerated drug discovery using annealing quantum computing technology. Traditionally, library design takes years, costs millions, and is limited to a narrow chemical space. Its Quantum-Aided Drug Design solution quickly identified a library of top candidate molecules for drug targets.[16]
- California-based Menten AI has been using quantum-classical hybrid approaches to design proteins not found in nature by leveraging synthetic biology, machine learning, and quantum computing. These new proteins have diverse applications in the pharmaceutical and chemical industries. Menten AI's work in de novo protein design has been advanced to live-virus testing for COVID therapeutics.[17]
- Mitsubishi Estate worked with Groovenauts, Inc. on a hybrid application that reduced carbon emissions during waste collection by nearly 60% in an area of Tokyo during both a shortage of waste collection workers and a government objective to lower emissions.[18]
- At the Port of Los Angeles, SavantX built a quantum application to optimize logistics at Pier 300. The Hyper Optimization Nodal Efficiency (HONE) quantum-powered AI engine increased the capacity and velocity of cargo movement at the port, doubling cargo handling equipment productivity and producing more predictable cargo flows. The hybrid application improved the pier's cargo handling efficiency by 60% and turnaround time for the trucks picking up cargo containers improved by 12%.[19]

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15. *Craig S. Smith, "Top 10 Quantum Computing Companies Making Change," Forbes, December 11, 2023, https://www.forbes.com/sites/technology/article/top-quantum-computing-companies/?sh=1097dc2d3a94.*
16. *POLARISqb, "POLARISqb Announces the Release of Quantum Aided Drug Design (QuADD): A Quantum Powered SaaS for Drug Discovery," EIN Presswire, May 31, 2023, https://www.einpresswire.com/article/636751835/polarisqb-announces-the-release-of-quantum-aided-drug-design-quadd-a-quantum-powered-saas-for-drug-discovery.*
17. *D-Wave Case Study, "Menten AI is Reimagining Biology with Quantum-Powered Protein Design," D-Wave website, 2021, https://www.dwavesys.com/media/exqjbloj/dwave_menten-ai_case_story_v10.pdf.*
18. *D-Wave Case Study, "Groovenauts and Mitsubishi Estate: Creating Sustainable Cities through Waste Collection Optimization," D-Wave website, 2021, https://www.dwavesys.com/media/bq5kh520/dwave_groovenauts_case_study_v3.pdf*
19. *NAM News Room, "How Quantum Computing Reorganized a Pier," National Association of Manufacturers, April 18, 2023, https://www.nam.org/how-quantum-computing-reorganized-a-pier-22712/*

- Pattison Food Group, the largest purveyor of food and healthcare products in western Canada, is building quantum-hybrid optimized applications to address e-commerce delivery, providing an 80% time savings.[20] The company also used a hybrid solver to reduce the time needed for one optimization task from 25 hours to just two minutes per week, saving both time and money.[21]

QUANTUM COMPUTING AND THE CLOUD

Since 2018, cloud access to a variety of quantum computing systems has broken down barriers for researchers, developers, and businesses, paving the way for additional innovation. Today, access is offered through cloud-based platforms such as AWS Braket, AWS Marketplace, Microsoft Azure, Google Cloud, and individual companies, including D-Wave's Leap™ real-time quantum computing cloud service.

Today, companies utilize cloud access to develop quantum annealing and quantum-hybrid applications for a variety of problems. For example:

- In Japan, an application was developed to optimize nurse scheduling by guaranteeing the appropriate staff was on call that considered variables such as shift parameters and personnel specialties.[22]
- Volkswagen used cloud access to build a paint shop scheduling application which was designed to optimize the order in which cars are being painted. This pilot application showed an 80% reduction in waste.[23]
- Artificial Brain won the myEUSpace award for its quantum-hybrid algorithm for optimizing real-time scheduling for multiple Earth Observation Satellites (EOS) enabled by cloud access. Bringing groundbreaking solutions in the integration of E.U. space data with cutting-edge technologies like Artificial Intelligence (AI) and quantum computing.[24]
- Recruit Group used cloud access to quantum to optimize the assignment of TV commercials to time slots, which resulted in reaching metrics that were 90% better than those achieved through manual scheduling methods. Millions of people in Japan will be able to watch TV commercials optimized by a hybrid application.[25]
- In Spain, CaixaBank used cloud access to build a hybrid application to optimize time-to-solution investment portfolio hedging and portfolio optimization in the insurance sector, decreasing compute time by up to 90% over the traditional solution. These time savings facilitated increased modeling complexity, allowing for a more dynamic model that is better adapted to real-time markets. It also optimized the invested capital while maintaining constant risk levels and improved the hedging decision-making process.[26]

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20. *Pattison Food Group Case Study, "Quantum in Production: Optimizing E-Commerce Logistics," D-Wave Website, https://www.dwavesys.com/media/2pnfscch/the-pattison-food-group_case_story_v7-1.pdf*
21. *Save on Foods, "Quantum Computing in Grocery," D-Wave YouTube, November 24, 2020, https://www.youtube.com/watch?v=Oi-fyFR5pWs (took out.*
22. *Kazuki Ikeda et al, "Application of Quantum Annealing to Nurse Scheduling Problem," Nature, Scientific Reports, September 6, 2019, https://www.nature.com/articles/s41598-019-49172-3*
23. *Sheir Yarkoni, "Volkswagen: Paint Shop Optimization with Quantum Annealing," Data: Labor Munich presentation, November 12, 2020, https://www.youtube.com/watch?v=Uenk1SF8NsI*
24. *Artificial Brain, "Quantum in Action: Efficient Earth Observation Satellites Mission Planning," D-Wave Webinar, June 22, 2023, https://www.youtube.com/watch?v=4BmPPZNgub8*
25. *D-Wave Case Study, "Quantum in Production: Maximizing TV Commercial Reach," D-Wave website, 2023 https://www.dwavesys.com/media/5tqm20yi/dwave_quantum-in-production_v4-1-1.pdf*
26. *D-Wave, "CaixaBank Group, D-Wave Collaborate on Innovative New Quantum Applications for Finance Industry," D-Wave press release, March 3, 2022*

QUANTUM COMPUTING TIMELINES AND QUANTUM TECHNOLOGY READINESS

Despite the growing list of applications, there are still two primary schools of thought regarding the timeline for quantum computing: some say the technology is still years away, while others argue that it is being used now. For example, a report by McKinsey stated that slow progress for hardware and software advancements means the technology may not be ready until 2035 or later.[27] It should be noted, however, that these experts are primarily looking at only the gate-model quantum computing modality.

There is growing evidence that quantum annealing can outperform classical computers for some optimization problems, either providing better, or in some cases faster answers. A 2023 paper from the Quantum Economic Development Consortium (QED-C) used a new benchmark to demonstrate quantum annealing's clear performance advantages for addressing optimization problems.[28] A study published in the April 2023 edition of Nature, found that annealing quantum computing applications more quickly addressed intractable optimization problems for a specific type of problem class found in logistics management, manufacturing, healthcare, finance, and more.[29]

Because different quantum technologies are advancing on different timelines and may have differing capabilities and strengths, several organizations have begun assessing technology readiness levels (TRL).

To illustrate, consider that NIST maintains that full-scale, error-corrected, gate-based computers stand at a TRL-1, meaning they are decades away from a commercial market. The agency puts noisy intermediate-scale quantum (NISQ) research (current gate-model) systems, which have some error correction and are available via the cloud, at a TRL-5, which is the R&D phase. NIST places commercially available annealing quantum computers at TRL-8/9, making them the highest TRL for quantum computers.[30] At the same time, the Jülich Supercomputing Center in Germany issued a TRL-5 ranking for gate-based systems with some error correction, and ranked quantum annealers at TRL-7/8.[31]

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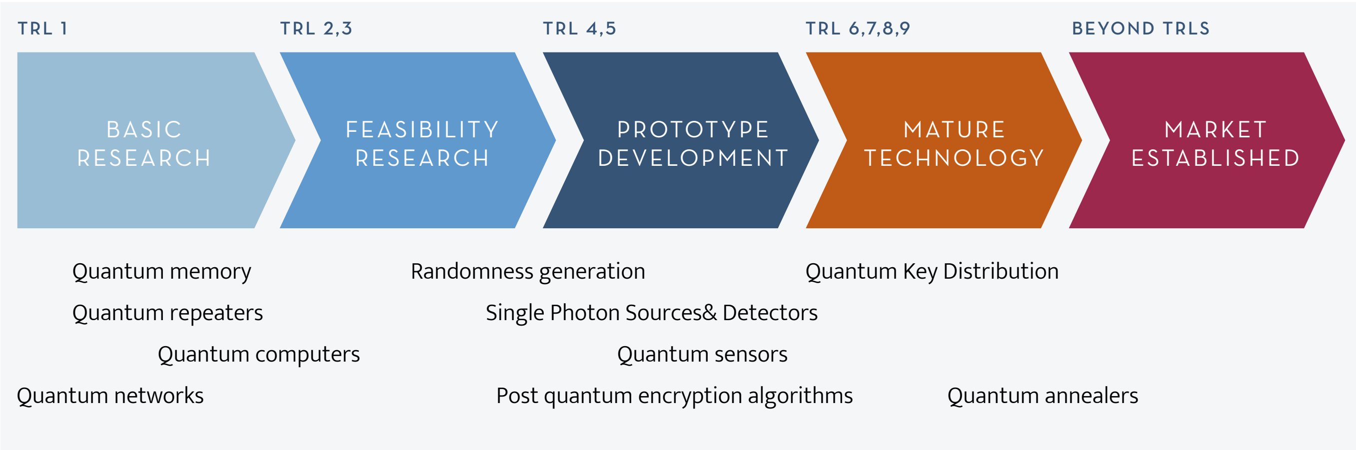
27. *McKinsey & Company, "What is Quantum Computing?" McKinsey Digital, May 1, 2023, https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-quantum-computing*
28. *Thomas Lubinski et al, "Optimization Applications as Quantum Performance Benchmarks," February 7, 2023, February 7, 2023, QED-C Website, 2302.02278.pdf (arxiv.org)*
29. *Andrew D. King et al, "Quantum critical dynamics in a 5,000-qubit programmable spin glass," Nature, April 19, 2023, https://www.nature.com/articles/s41586-023-05867-2*
30. *Barbara Goldstein, "The Dream of a Common Language: international standards for the quantum economy," Department of Commerce National Institute of Standards and Technology webinar, June 23, 2021, https://www.itu.int/en/ITU-T/webinars/20210623/Documents/Goldstein%20Final.pdf?csf=1&e=GdALdj*
31. *Jülich Supercomputing Centre (JSC) Institute for Advanced Simulation (IAS), "Technology Readiness Level of Quantum Computing Technology (QTRL)," Jülich Forschungszentrum website, July 19, 2022, https://www.fz-juelich.de/en/ias/jsc/about-us/structure/research-groups/qip/technology-readiness-level-of-quantum-computing-technology-qtrl?expand=translations,fzjsettings,nearest-institut*

FIGURE 1: STANDARDIZATION READINESS AND ACTIVITY



Source: Harmonization of Terminology in Standards for Quantum Technology, June 23, 2021, Barbara Goldstein, Associate Director, Physical Measurement Laboratory, NIST Program Manager, NIST on a Chip, Slide 16 (excerpt) https://www.itu.int/en/ITU-T/webinars/20210623/Documents/Goldstein%20Final.pdf?csf=1§e=GdALdj

THE GLOBAL QUANTUM LANDSCAPE

As we look at the global quantum landscape, we need to consider both the private and public sectors.

PRIVATE SECTOR

Quantum patents can be a good indicator of industry innovation. Globally, there are nearly 150 research and private sector players engaged with quantum computing technology, with the U.S. holding the largest number of patents for quantum technologies, and China coming in second.[32] Many of these patents are held by smaller start-up companies.

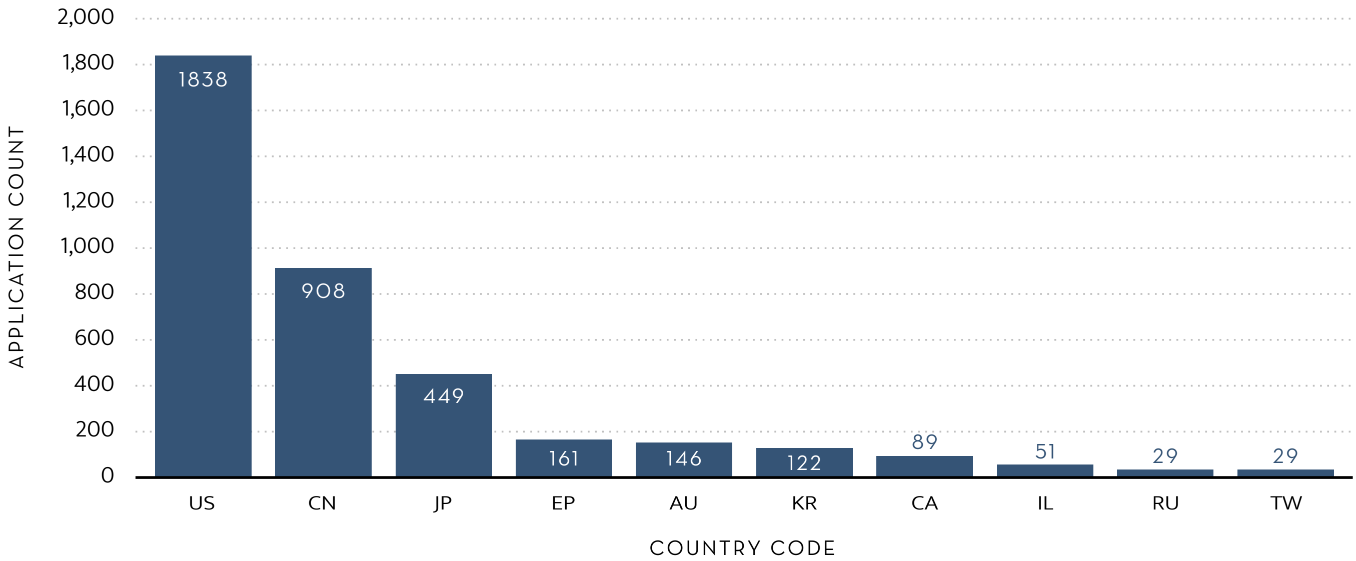
TABLE 2: TOP 10 QUANTUM COMPANIES RANKED ACCORDING TO THEIR NUMBER OF QUANTUM PATENTS

1	IBM (1323 patents)
2	Google (762 patents)
3	D-wave (501 patents)
4	Microsoft (496 patents)
5	Northrop Grumman (262 patents)
6	Origin of Quantity (234 patents)
7	Intel (221 patents)
8	Baidu News (186 patents)
9	IonQ (164 patents)
10	Rigetti (110 patents)

Source: Quantum Zeitgeist, https://quantumzeitgeist.com/top-10-quantum-companies-ranked-according-to-their-number-of-quantum-patents/

32. *Elliot Mason, "Quantum patent trends update: 2022," QED-C Blog Post, February 13 2022, https://quantumconsortium.org/blog/quantum-patent-trends-update-2022/*

FIGURE 2: QUANTUMN COMPUTING PATENTS: TOP 10 COUNTRIES



Source: Elliott Mason, Quantum patent trends update: 2022, QED-C Blog Post figure 1, February 13, 2023, https://quantumconsortium.org/blog/quantum-patent-trends-update-2022/

It should also be noted that no single country holds the entire quantum computing supply chain within its borders.[33] According to the QED-C, the U.S. quantum computing industry is too small to support a robust commercial scale supply chain that produces items such as specialty parts, cryogenics, and chip fabrication.[34] Therefore, international agreements must include the protection of access to technologies found across the entire quantum computing supply chain to address U.S. quantum industry needs.

PUBLIC SECTOR

As of May 2023, worldwide government investments in exploring quantum science and technology totals over $36 billion.[35] Countries estimated to have already invested more than $1B include:

- China $15.3 B
- United Kingdom: $4.3B
- United States: $3.75B
- Germany $3.1B
- France; $2.2B
- Russia: $1.45B

Many foreign quantum programs are actively supporting commercialization efforts that expressly encourage near-term quantum and quantum-classical hybrid application development. They also accelerate educating a quantum-ready workforce, expressly calling out the need to include annealing quantum computing, gate-model, and hybrid in workforce development programs. Selected examples of global quantum initiatives include:

33. *Karen Howard, "The Quantum Leap Hinges on Worker Skills and Supply Chain Limits," U.S. Government Accountability Office blog, October 20, 2021, https://www.gao.gov/blog/quantum-leap-hinges-worker-skills-and-supply-chain-limits*
34. *QED-C blog post, "The opportunities and constraints of the quantum supply chain," June 26, 2022, https://quantumconsortium.org/blog/the-opportunities-and-constraints-of-the-quantum-supply-chain/*
35. *Maninder Kaur, "Overview of Quantum Initiatives Worldwide 2023," QURECA report, July 19, 2023, https://qureca.com/overview-of-quantum-initiatives-worldwide-2023/*

- **China:** In addition to committing to provide $15.3 billion in public funds[36] toward quantum technology, China has released a new generation of a quantum computing cloud platform that "enables researchers to perform complex computational tasks in the cloud and the public to experience quantum computing at the speed of microseconds."[37]
- **United Kingdom:** The U.K. is currently looking at the feasibility of developing quantum applications within an 18-month or less timeframe for a variety of industries, including manufacturing, transportation, and financial services.[38] The U.K.'s 10-year Quantum Strategy explicitly includes quantum annealing and gate-model quantum computing, and focuses on application development, talent development, user access to quantum systems for researchers and businesses, and focused funding for commercialization.[39]
- **Canada:** The Industry Committee of the Canadian House of Commons recommended a quantum sandbox program where different government agencies come together to identify problems that could be solved using near-term quantum applications.[40] This will accelerate commercialization and address public sector challenges. The Canadian national quantum strategy also has a three-pillar focus: research, talent, and commercialization.[41]
- **Australia:** The Australian government released a national quantum strategy and set a $1B funding level in May 2023.[42] The New South Wales government has announced looking at quantum computing to optimize its transportation system,[43] and the Australian army built applications enabling autonomous vehicles to optimize last-mile resupply operations for defense and emergency response.[44]
- **Japan:** The Japanese government supported building quantum applications to reduce CO_2 emissions during waste collection, optimize construction projects, and improve tsunami evacuation routes.[45]
- **European Union and E.U. Countries:**
  - German officials and E.U. Commissioners discussed the need for near-term quantum applications at a January 2022 event in Jülich, Germany.[46]

36. *Kaur, "Overview of Quantum Initiatives Worldwide 2023" 2023, https://qureca.com/overview-of-quantum-initiatives-worldwide-2023/*
37. *Zhang Kaiwei, "China unveils new quantum computing cloud platform," People's Daily Online, May 29, 2023, http://en.people.cn/n3/2023/0529/c90000-20024986.html*
38. *Innovate UK, "Feasibility Studies in Quantum Computing Applications," Innovate UK Webinar, February 14, 2023, https://iuk.ktn-uk.org/events/quantum-competition-briefings-computing/*
39. *Government of the United Kingdom: Department for Science, Innovation and Technology, "National Quantum Strategy," UK Government publication, March 2023, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1142942/national_quantum_strategy.pdf*
40. *Joël Lightbound, "How Can Canada Remain a Leader in the Global Quantum Marathon?" Report of the Standing Committee on Industry and Technology, September 2022, https://www.ourcommons.ca/DocumentViewer/en/44-1/INDU/report-6/*
41. *Innovation, Science and Economic Development Canada, "Overview of Canada's National Quantum Strategy," Government of Canada website, January 13, 2023, https://ised-isde.canada.ca/site/national-quantum-strategy/en*
42. *Australian Government's Department of Industry, Science and Resources, "National Quantum Strategy," Australian Government website, May 3, 2023, https://www.industry.gov.au/publications/national-quantum strategy#:~:text=The%20National%20Quantum%20Strategy%20is,the%20opportunities%20of%20quantum%20technologies*
43. *HPC Wire, "Australian Government Enlists Quantum Computing to Improve Transportation System," April 12, 2021, https://www.hpcwire.com/off-the-wire/australian-government-enlists-quantum-computing-to-improve-transportation-system/*
44. *David Garvin, "NEC Australia: Solving the Last Mile Resupply Problem," D-Wave Qubits 2021, November 5, 2021, https://youtu.be/BM23FpwlAYk*
45. *Masayuki Ohzeki, "Quantum Technology Innovation hub: Tohoku University," D-Wave YouTube, January 31, 2023, https://www.youtube.com/watch?v=UNYvS8mlaZg&list=PLPvKnT7dgEsueC42YKXifcQjWAlG0kcKm&index=22*
46. *The Jülich Supercomputing Centre (JSC), "Europe's First Quantum Computer with More Than 5,000 Qubits Launched at Jülich," Forschungszentrum Jülich YouTube, January 17, 2022, https://www.youtube.com/watch?v=ZY7pCp16DMA*

- E.U. Commission: The Next Applications of Quantum Computing Program aims to boost quantum application development.[47]
- Uptown Basel in Switzerland opened a new Quantum Hub focused on commercialization.[48]
- Denmark: Denmark's Ministry of Higher Education and Science released a Strategy for Quantum Technology that creates a Quantum Excellence Center for developing and testing quantum algorithms and supporting hybrid applications.[49]

In the U.S., the National Quantum Coordination Office (NQCO), which is located in the White House Office of Science and Technology Policy (OSTP), released its annual report highlighting areas where the U.S. has engaged with allied nations, including bilateral collaboration agreements.[50] The majority of these collaborations are solely academic in nature.

U.S. POLICY LANDSCAPE:

NATIONAL QUANTUM INITIATIVE (NQI) ACT– THE NEED FOR REAUTHORIZATION AND EXPANSION

The NQI, enacted in 2018, was the first comprehensive U.S. quantum policy program to establish cross-government coordination, encourage collaboration, and enable engagement between researchers, national labs, and industry.

The NQI has been an important vehicle for moving our country toward advancing quantum technologies, primarily through the creation of federal offices, committees, and consortia within the federal government. Since 2018, NQI efforts have focused on setting up quantum centers and on fundamental science, rather than near-term applications, and the quantum programs are not inclusive of all quantum computing technologies. For example, within the Department of Energy (DOE), the NQI created five quantum centers, led by national laboratories, which focus on different quantum information science (QIS) areas such as sensing, communications, networking, and computing. Industry engagement has been limited since the centers have only just begun their work, and much of the work has been focused on hardware and not the software stacks.

In addition, the Act established a National Quantum Initiative Advisory Committee (NQIAC) to review and provide recommendations on how to revise U.S. quantum programs. Established in 2019, the original NQIAC membership reflected a broad background of academia, industry, and government, but fell short of encompassing the wide technology landscape of the quantum industry. In 2022, the NQIAC membership was narrowed to primarily academia and research, which constrained industry's ability to help shape U.S. quantum programs and provide up-to-date information on scientific breakthroughs, capabilities, and commercial products.

47. *Next ApplicationS of Quantum Computing Program, "Boosting practical applications of quantum computing in the NISQ era," European Union Commission project, September 1, 2020, https://cordis.europa.eu/project/id/951821*
48. *QuantumBasel, "Democratizing the power of quantum," QuantumBasel website, June 18, 2023, https://quantumbasel.com/*
49. *Denmark's Ministry of Higher Education and Science, "Strategy for Quantum Technology," Quantum Computing Report, June 24, 2023, https://quantumcomputingreport.com/overviews-and-recommendations-for-the-quantum-ecosystems-in-canada-denmark-and-norway/*
50. *Subcommittee on Quantum Information Science; Committee of Science of the National Science and Technology Council, "National Quantum Initiative Supplement to the President's FY2023 Budget, January 2023, https://www.quantum.gov/wp-content/uploads/2023/01/NQI-Annual-Report-FY2023.pdf.*

RECOMMENDED POLICIES TO BE INCLUDED IN NQI REAUTHORIZATION AND U.S. QUANTUM PROGRAMS

The call for developing and adopting near-term quantum computing applications represents an important shift in congressional action around quantum computing. Following is a breakdown of the primary policy opportunities before Congress, including recommendations for how the NQI should be expanded.

- TECHNOLOGICAL READINESS LEVELS (TRLS)
  Including an objective government TRL assessment in the NQI reauthorization would create a consistent standard to objectively review quantum technology. Such an assessment should break down the two quantum computing approaches (annealing and gate-model), different qubit architectures (ion traps, superconducting, photonic, neutral spin atoms, etc.), and quantum-classical hybrid applications. Regular assessments every two to three years will ensure TRLs reflect new scientific breakthroughs and provide needed oversight on advancements of the technology.
- QUANTUM USER EXPANSION FOR SCIENCE AND TECHNOLOGY (QUEST) PROGRAM.
  The QUEST program encourages and facilitates access to commercial quantum computing hardware through cloud platforms for research purposes. In the CHIPS Act (Public Law 117-167), QUEST was authorized at approximately $30M annually for five years, less than the original legislation's funding levels, which increased from $30M to $100M over a five-year period.[51] In the FY24 House Energy and Water Appropriations Bill, QUEST's current funding recommendation is up to $15M in year one, which was included in the FY24 appropriations package. As systems advance and researchers demand additional access to commercial systems, the QUEST program will need to expand. At a minimum, QUEST should be funded up to $30M annually, and increased funding will be needed for future years.
- QUANTUM SANDBOX FOR NEAR-TERM APPLICATIONS ACT (S. 1439 AND H.R. 2739)
  Bipartisan legislation, introduced by Senators Marsha Blackburn (R-Tenn.) and Ben Ray Luján (D-N.M.) and Representatives Jay Obernolte (R-Calif.) and Haley Stevens (D-Mich.), amends the NQI by creating a "quantum sandbox," an environment where innovators can develop and test demonstrations, proofs of concepts, and pilot applications of near-term quantum technology in less than 24 months. This program must be inclusive of the wide variety of quantum computing modalities and qubit architectures. It will help accelerate U.S. commercialization of quantum technology by enabling the government and private sector to work together to develop and deploy quantum applications to solve critical real-world problems.[52] Similar programs have been discussed in Canada, and funding of application development has begun in the U.K., Japan, and other regions. Other policies that are identifying near-term uses for quantum computing include the Wildfire Tech

51. *117th Congress, "Quantum User Expansion for Science and Technology Program at the Department of Energy (QUEST), H.R. 1837, March 11, 2021, https://www.congress.gov/117/bills/hr1837/BILLS-117hr1837ih.pdf*
52. *118th Congress, "Quantum Sandbox for Near-Term Applications Act of 2023," S. 1439, May 5, 2023, https://www.blackburn.senate.gov/2023/5/blackburn-luj-n-lead-bill-to-boost-quantum-computing-applications-in-u-s*
    House bill is H. R. 2739, https://www.congress.gov/bill/118th-congress/house-bill/2739/text?s=1§r=11§q=%7B%22search%22%3A%5B%22Hr+9%22%5D%7D

Demonstration, Evaluation, Modernization, and Optimization (DEMO) Act (H.R. 4235) which is focused on emergency response[53] and the Grid Resilience Innovation and Development (GRID) Act (S. 3115).[54]

- FY24 NATIONAL DEFENSE AUTHORIZATION ACT (NDAA) – (P.L. 118-31)
  In the FY21 NDAA, Congress tasked the Department of Defense (DOD) with identifying problems that could be solved by quantum computing within three years while being inclusive of the range of quantum technologies.[55] To date, DOD has not published reports nor indicated it has taken any action. Within Section 231 of the FY24 NDAA (P.L. 118-31) DOD is directed to work with a federally funded research and development center to create a pilot program within 24 months focused on near-term quantum applications that include all quantum technologies. This pilot program would help accelerate the use of today's technology.[56]

- QUANTUM IN PRACTICE ACT (S.969 & H.R. 1748)
  Bipartisan legislation to increase near-term uses of quantum technology was introduced by Reps. Randy Feenstra (R-Ind.) and Haley Stevens (D-Mich.) and Sens. Todd Young (R-Ind.) and Raphael Warnock (D-Ga.). The bill expands the Department of Energy's (DOE) focus to include quantum molecular simulations and modeling in federal scientific research, which will allow experts to study chemical elements and reactions more accurately.[57] This research, which could benefit a variety of industries including life sciences and agriculture, was included in the NQI reauthorization within the House Science Committee.

- DOMESTIC QUANTUM INFRASTRUCTURE
  Policies supporting integrating quantum annealing and gate-model modalities into high-performance computing (HPC) data centers are necessary to build quantum-classical hybrid applications that can tackle complex problems. Future access to these systems will be through integrated HPC and quantum data centers. Growing competition for these centers around the globe is evidenced by techUK's Future to Compute report.[58] Ensuring quantum computing is within an HPC data center structure is an important first step for addressing domestic infrastructure needs and should be prioritized in the NQI reauthorization. Moreover, the domestic chip fabrication for increased rapid prototyping for commercial-sized chips is needed. This funding could be incorporated into the CHIPS research and development funding or via the manufacturing center recommended in S.2450.[59]

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53. *118th Congress, "Wildfire Tech Demonstration, Evaluation, Modernization, and Optimization (DEMO) Act," HR 4235, June 21, 2023, https://youngkim.house.gov/media/press-releases/young-kim-leads-wildfire-tech-demo-act*
54. *118TH Congress, "Grid Resilience Innovation and Development (GRID) Act," S. 3115, October 24, 2023, Cornyn, Padilla Introduce Bill to Help Make U.S. Electric Grid More Resilient | Senator Cornyn (senate.gov)*
55. *116th Congress, "William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021," Public Law 283, https://www.govinfo.gov/content/pkg/PLAW-116publ283/html/PLAW-116publ283.htm*
56. *118th Congress, "National Defense Authorization Act for Fiscal Year 2024," H.R.2670, July, 2023, Became Public Law No. 118-31 on 12/22/2023, https://www.congress.gov/bill/118th-congress/house-bill/2670*
57. *118th Congress, "Quantum in Practice Act," S.969, March 23, 2023 https://www.congress.gov/118/bills/s969/BILLS-118s969is.pdf . House bill is H.R. 1748 https://www.congress.gov/bill/118th-congress/house-bill/1748/text*
58. *TechUK report, "Future of Compute Review," teckUK website, March 6, 2023, https://www.techuk.org/resource/future-of-compute-review-report-published.html*
59. *118th Congress, "Legislation to Improve Coordination for National Quantum Initiative Programs," S. 2450, July 20, 2023, https://www.congress.gov/bill/118th-congress/senate-bill/2450?s=1§r=1*

CONGRESSIONAL ACTION ON NQI REAUTHORIZATION

On November 3rd 2023, Chairman Frank Lucas (R-Okla.) and Ranking Member Zoe Lofgren (D-Calif.) introduced bipartisan legislation in the House Science Committee to reauthorize and extend the NQI.[60] The bill advances near-term quantum technology by incorporating many of the policy positions laid out in this paper such as pushing for additional commercialization efforts, support for industry engagement within U.S. quantum programs, a dedicated near-term quantum application development program, and an overarching inclusion of all quantum computing technologies (annealing, gate-model, and quantum-hybrid). This explicit inclusion will now align the U.S. government with other global quantum programs.

The expanded NQI language also includes greater engagement across government agencies by bringing the National Oceanic and Atmospheric Administration, NASA, the Department of Homeland Security, the Department of State, and others into quantum programs. Rep. Deborah Ross' bill, H.R. 3987, includes greater coordination to identify how other agencies can benefit from quantum technologies.[61] Including both scientific parts of the government and end users and negotiators of international agreements will help balance U.S quantum efforts between near-term uses and longer-term academic advancements.

While the proposed NQI legislation does not specifically include the Quantum Sandbox bill, it does contain testbed language to develop and deploy demonstrations and proof of concepts for quantum applications with a focus on commercialization in quantum programs and international agreements. In addition, it incorporated the Quantum in Practice Act which expands the DOE's efforts to include simulations and modeling.

What is missing, however, is adding industry representatives who are knowledgeable about commercialization and near-term application capabilities to the National Quantum Initiative Advisory Committee. Other areas of improvement include ensuring new quantum programs can begin work in a timely manner, increased transparency and reporting, and including small businesses, many of which are leaders in quantum innovation, in these programs.

At the time of this paper's publishing, the legislation is moving through the House of Representatives. However, the Senate version is not yet publicly available, and the timing for Senate action is currently unknown.

TALENT DEVELOPMENT IS CRITICAL TO QUANTUM COMPUTING'S SUCCESS

Policy changes are necessary to ensure the U.S. creates a quantum-ready workforce to help solidify our country's leadership in quantum innovation. In 2022, the National Science & Technology Council published a national strategic plan that evaluated the labor market in an effort to "prepare more people for jobs with quantum technology, enhance STEM education at all levels, accelerate exploration of quantum

60. *Committee on Science, Space & Technology, "Full Committee Markup of H.R. 6213 & H.R. 6131, November 29, 2023, Full Committee Markup of H.R. 6213 & H.R. 6131 - Markups - House Committee on Science Space & Tech - Republicans*
61. *118th Congress, "Leveraging Quantum Computing Act," H.R.3987, June 9, 2023, https://www.congress.gov/bill/118th-congress/house-bill/3987?s=1&r=2*

frontiers, and expand the talent pool for industries of the future."[62]

Historically, talent programs have focused on theoretical physics departments. A robust quantum-ready workforce will notably also require work with other disciplines. A QED-C workforce assessment survey emphasizes the need for broader engagement with other fields such as data science, algorithm development, cryogenics, and engineering. The survey also found that PhDs are not necessary for many positions within quantum technology companies.[63] Talent should be broken down as follows:

- Those who will build the systems and facilities to house the systems.
- Those who will build and manage the software stacks and security of these technologies.
- End users, including those who will educate users on both the technology benefits and which problems are best for which systems.

Despite cross-border academic engagement and cultivating enthusiasm in students for STEM from an early age, the U.S. would benefit from multi-disciplinary talent engagement. One policy solution is to expand the NQI to include funding for talent programs permitting students from a variety of fields to access quantum training courses created by industry. For example, students who are studying business optimization could benefit from curricula and training on quantum computing applications that address business problems. Many of these training programs are provided by industry and are available online. A joint training program between British Columbia-based Quantum Algorithms Institute and D-Wave, which allows students to access industry training programs, will expedite a quantum-ready workforce.[64] Hands-on quantum computing training programs and access to quantum systems are necessary to help the U.S. accelerate talent development. Focused programs can also be aimed at upskilling the government workforce to better utilize the power of quantum computing technologies.

THIRD PARTIES SUPPORT RECALIBRATING U.S. QUANTUM PROGRAMS

As Congress considers policies that will create a path forward for our U.S. quantum technology programs, think tanks, tech policy organizations, and others are increasingly calling on the government to build quantum applications that could solve challenging problems using today's technology. A report authored by the Center for Data Innovation made the case for U.S. investment in near-term quantum application programs.[65] A recommendation for a communication resiliency quantum sandbox program was included in the President's National Security Telecommunications Advisory Committee.[66]

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62. *Subcommittee on Quantum Information Science Committee on Science of the National Science & Technology Council, "Quantum Information Science and Technology Workforce Development National Strategic Plan," QIST Workforce Development report, February 2022, https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf*
63. *Ciaran Hughes et al., "Assessing the Needs of the Quantum Industry," Fermilab-Pub-21-381-T, August 25, 2021 https://arxiv.org/pdf/2109.03601.pdf*
64. *Knowlton Thomas, "Pilot Program Launches to Train 'Quantum-Ready Workforce' in Canada," TechTalent.ca, May 19, 2023, Pilot Program Launches to Train 'Quantum-Ready Workforce' in Canada - Tech Talent Canada*
65. *Hodan Omaar, "Why the United States Needs to Support Near-Term Quantum Computing Applications," Information Technology & Innovation Foundation Center for Data Innovation, April 27, 2021, https://itif.org/publications/2021/04/27/why-united-states-needs-support-near-term-quantum-computing-applications/*
66. *The President's National Security Telecommunications Advisory Committee, NSTAC Report to the President on Communications Resiliency, May 6, 2021, https://www.cisa.gov/sites/default/files/publications/NSTAC%20Report%20to%20the%20President%20on%20Communications%20Resiliency_0.pdf*

In the area of national security and defense, the Advanced Technology Academic Research Center (ATARC) released its report highlighting quantum applications for today's military.[67] Large government contractors like Deloitte have stated that public sector leaders can build pilots and simulations using quantum technologies to solve optimization problems, improve the accuracy of groundwater mapping, and search through unsorted data.[68]

There is also support for identifying near-term applications within the U.S. government. In March 2023, the Center for Strategic & International Studies hosted an event in which Rima Oueid, Senior Commercialization Executive at the DOE Office of Technology Transitions, described the energy grid as a good "sandbox" to prioritize quantum applications development that would tackle grid optimization and contingency analysis.[69] The National Science Foundation has funded the Center for Quantum Technologies, which brought together Purdue University, Indiana University at Bloomington, the University of Notre Dame, and Indiana University Purdue University-Indianapolis to examine hardware and software advancements across the variety of systems. The research, which began in May 2023, encompasses a variety of different research projects including optimization using annealing technology as well as research on superconducting and photonic qubit architectures.

CONCLUSION

Since the NQI expired in September 2023, there is a need for Congress to act. Reauthorization of the NQI provides the opportunity to make modifications to the federal government's current quantum computing programs to better position the country to be a global leader in quantum technology. Reauthorization and expansion of the NQI, coupled with additional policies, will close the gap that has emerged between the pace of quantum technological innovation and the domestic policies that guide the quantum industry.

Since different quantum computing approaches have different capabilities and advance at different paces, it is vital that the current government mindset evolves to include annealing quantum computing, gate-model, and quantum-classical hybrid modalities. Doing so will foster solutions to pressing public sector problems like infrastructure development, emergency response planning, sustainability efforts, and electrical grid resilience.

Such a shift will move the U.S. closer to global leaders like the U.K., Australia, E.U., Germany, Japan, and Canada, which have invested in near and long-term quantum technology.

By adding talent development training, user access programs, and international commercialization agreements, the next five years of the NQI will pave the way for a robust

67. *ATARC Quantum Working Group, "Applied Quantum Computing for Today's Military," Advanced Technology Academic Research Center, May 2021, https://atarc.org/wp-content/uploads/2021/05/ATARC-Military-Paper-by-Quantum-Working-Group.pdf*
68. *Scott Buckholz et al, "Sensing the future of quantum: How quantum computing could benefit the public sector," Deloitte Insights, February 22, 2023, https://www2.deloitte.com/us/en/insights/industry/public-sector/future-of-quantum-technology-public-sector.html*
69. *Center for Strategic & International Studies, "The Future of Quantum - Building a Global Market," CSIS event, March 20, 2023, https://www.youtube.com/watch?v=_fKzeDPx5D8*

domestic quantum industry and strong U.S. quantum computing programs that are realizing the benefits of near-term quantum technology across the federal government.

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Based in Washington, D.C., and part of The Progressive Policy Institute, The Innovation Frontier Project explores the role of innovation in U.S. political reform.

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