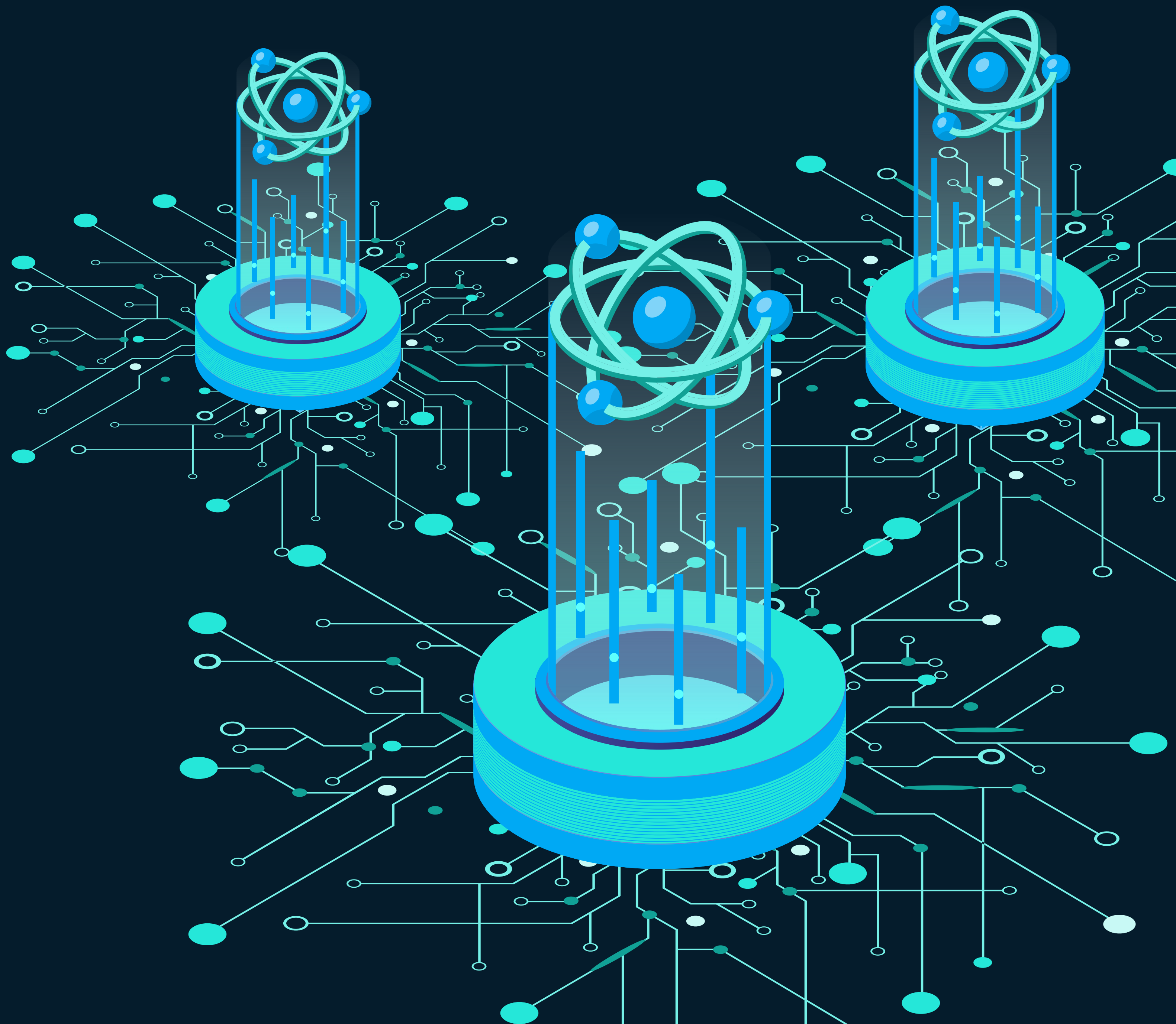
McKinsey Digital

Quantum Technology Monitor

April 2024



What can you find in this report?

- ✓ Continuously evolving overview of the quantum technology (QT) market (including investments, competitive landscape, and economic activities), covering quantum computing (QC), quantum communication (QComm), and quantum sensing (QS); see the next page for definitions of these areas
- ✓ Overview of the **maturity of the QT ecosystem and the use of QT in the broader industry context,** based on current application of the technology and patent and publication activity
- ✗ **Definitive and exhaustive list** of the start-up, investment, and economic activities in the QT space

New additions to the Monitor

- Updated insights on the investment landscape (pp. 10–25)
- Revised internal market size and value at stake (pp. 26–30)
- Technological breakthroughs in QT (pp. 31–33)
- Global research and IP landscape (pp. 34–42)
- Regional perspective on quantum technology (QT) in North America (pp. 43–45), Asia (pp. 46–52), and Europe (pp. 53–60)
- Deep dive on QT innovation clusters (pp. 61–66)
- Technology deep dives for QC including quantum control and benchmarking (pp. 67–84)
- Perspectives on technology and applications for QComm (pp. 85–90), QS (pp. 91–97), and quantum and AI (pp. 98–100)

Note: The Quantum Technology Monitor 2024 is based on research from numerous data sources (including, but not limited to, CapitalIQ, Crunchbase, PitchBook, Quantum Computing Report, expert interviews, and McKinsey analysis); minor data deviations may exist due to updates of the respective databases; data captured is up to and including December 2023.

Definitions: Quantum technology encompasses the three subfields of computing, communication, and sensing.

Quantum computing (QC)
is a new computing paradigm leveraging the laws of quantum mechanics to provide significant performance improvement for certain applications and enable new territories of computing compared to existing classical computing.

Quantum sensing (QS)
is a new generation of sensors based on quantum systems that provide measurements of various quantities (eg, electromagnetic fields, gravity, time) that are orders of magnitude more sensitive than classical sensors.

Quantum communication (QComm)
is the secure transfer of quantum information[1] across distances and could ensure security of communication even in the face of unlimited (quantum) computing power.[2]

[1]Quantum information differs from classical information, where information is stored as quantum states in qubits. Qubits are the unit of information for QC and are an extension of the classical bit (the unit of information for classical computing)
[2]Quantum cryptography draws on the exchange of a secret key to encrypt messages based on the quantum mechanical phenomenon of entanglement. Unlike any classical cryptographic protocol, it is in principle not possible to “eavesdrop” on messages exchanged with quantum cryptography without detection. However, early implementations have been shown to have some weaknesses caused by, for example, physical implementations of the protocols.

Source: McKinsey analysis

Quantum Technology Monitor 2024 overview (1/2)

Private and corporate funding for QT start-ups slowed from prior years, while a strong flow of public funding was announced by several governments, totaling ~$42 billion. The ecosystem continues to progress toward unlocking an estimated economic value of ~$2 trillion by 2035.

+XX% Compared to previous year

Investments and ecosystem

$8.5B +25% YOY
total cumulative global QT start-up investment

367 +5% YOY
start-ups in the QT ecosystem

$42B +26% YOY
total government investment announced

Quantum technology market size scenarios for 2035 and 2040

Based on existing development road maps and assumed adoption curve

	Quantum computing	Quantum communication	Quantum sensing
2035	$28B–$72B	$11B–$15B	$0.5B–$2.7B
2040	$45B–$131B	$24B–$36B	$1B–$6B

Potential economic value from quantum computing in 2035

~$0.9T–$2T

potential economic value across four industries by 2035: chemicals, life sciences, finance, and mobility[1]

[1]Economic value is defined as the additional revenue and saved costs that the application of QC can unlock in all industries. These four industries are the most likely to realize this value earlier than other industries; therefore, they are examined in more depth.

Quantum Technology Monitor 2024 overview (2/2)

The momentum in the QT ecosystem will be fueled by the robust talent and patent activities. Key players make groundbreaking innovations, thereby driving the QT ecosystem forward toward quantum advantage.

+XX% Compared to previous year

Quantum computing

- 261 start-ups
- $6.7 billion investment

Quantum communication

- 96 start-ups
- $1.2 billion investment

Quantum sensing

- 48 start-ups
- $0.7 billion investment

Companies pursuing two or more quantum technologies simultaneously: 38

Technological breakthroughs in 2023

Quantum computing

Quantum error-correction proposals and demonstrations by large players accelerate timelines toward large-scale, fault-tolerant quantum computing

Quantum communication

Improved performance for quantum key distribution, and demonstration of longer transmission distances and increased data rates for quantum networks

Quantum sensing

Development of new techniques to improve the sensitivity of quantum sensing devices

Scientific progress

4,763 +1% YOY

QT-related patents granted in 2022[1]

42,155 –4.5% YOY

QT-related publications in 2023

Quantum-capable talent

55 +10% YOY

QT master's degree programs

195 +8.3% YOY

universities with QT research groups

[1] Data as of Jan 2024, retrieved from Patsnap database; patent data shown is for 2022, as data for 2023 is not yet completely reported.

Executive summary (1/3)

Quantum technology investment landscape

There was continuous momentum and a huge amount of funding announced in 2023, but decreased private investments and a reduced number of new start-ups.

- Total annual QT start-up investment decreased by 27% YoY to $1.7 billion, a decline smaller than the 38% decline in all start-up investment worldwide. Investments in all quantum technologies declined, with the largest decline in quantum sensing.
- Fewer new QT start-ups were created in 2023 (–44% YoY, to 13), with the majority (62%) of funding going to companies founded five or more years ago.
- Public investments continue strong: Germany, the United Kingdom, South Korea, and India announced significant new funding for QT development, bringing the global public funding total to date to ~$42 billion.

Internal market size and value at stake

- Our updated analysis shows the market size for 2035 for quantum computing is expected to reach $28 billion to $72 billion; for quantum communication, $11 billion to $15 billion; and for quantum sensing, $0.5 billion to $2.7 billion.
- Our updated analysis on value at stake also shows the four industries likeliest to see the earliest economic impact from quantum computing—chemicals, life sciences, finance, and mobility—stand to potentially gain up to $2 trillion in value by 2035.

Executive summary (2/3)

Technological breakthroughs

Pathbreaking milestones achieved in error mitigation and correction promise to significantly shorten timelines for the advent of universal fault-tolerant quantum computers.

- Quantum error mitigation, correction proposals, and logical qubit demonstrations by Alice & Bob, Amazon (AWS), IBM, QuEra, Microsoft, Quantinuum, and IonQ show promise toward large-scale, fault-tolerant quantum computing with potentially accelerated timelines for quantum advantage.
- For quantum communication, researchers are improving the performance for quantum key distribution and demonstrating longer transmission distances and increased data rates using innovative technologies.
- Quantum sensing sees continuous development of promising new techniques that improve the sensitivity of quantum sensor technology based on diamond nitrogen-vacancy (NV) centers.

Quantum talent

There were 4,763 QT-related patents granted in 2022, 1% more than the number of patents granted in 2021.

QT publishing decreased in 2023 (–4.5% YOY), with 42,155 QT-related publications worldwide, with contributions led by EU-based scientists, followed by China and the United States.

As universities continue to offer more QT programs worldwide, the European Union continues to lead in the number of gradates in QT-relevant fields.

- The number of universities with QT programs increased 8.3%, to 195, while those offering master's degrees in QT increased by 10%, to 55.
- The European Union and the United Kingdom have the highest number and density, respectively, of graduates in QT-relevant fields, followed by India in number and the European Union in density.

Source: Press search, Patsnap

Executive summary (3/3)

Quantum in North America, Asia, and Europe

Quantum innovation clusters

This edition of the Quantum Technology Monitor includes details on the quantum ecosystem within various continents and regions. Key figures, policies, news, and hubs of information can be found for selected countries around the world in North America, Asia, and Europe.

With the large amounts of announced public funding for quantum technology development, innovation clusters become critical for facilitating close collaboration between government, academia, and industry for advancing both the technology and key use cases for quantum technologies.

- Key stakeholders of an innovation cluster are identified along with their roles
- Key enablers of an innovation cluster are identified

Technology deep dives

Quantum and AI

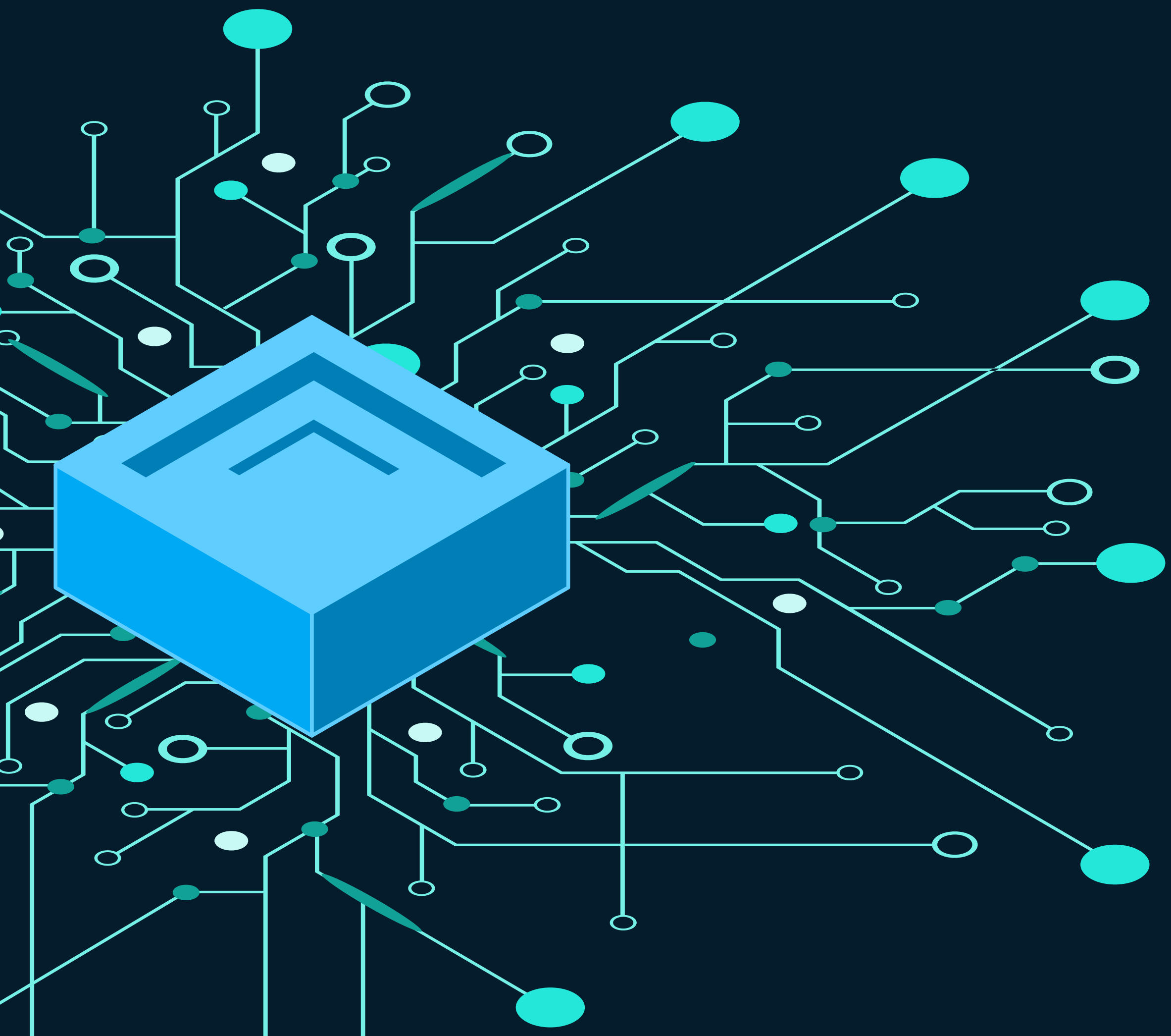
A refresh of the start-up ecosystems, value chain, and technological deep dives for each quantum technology, including highlights from analyses:

- Quantum computing: Quantum control and benchmarking
- Quantum communication: Milestones for secure quantum communication and timeline of susceptibility to quantum attack
- Quantum sensing: Key use cases by industry

Brief outline of how the synergy of quantum technologies and AI have the potential to create larger impact and how the technologies stand to benefit from each other's development.

Source: Patsnap; McKinsey analysis

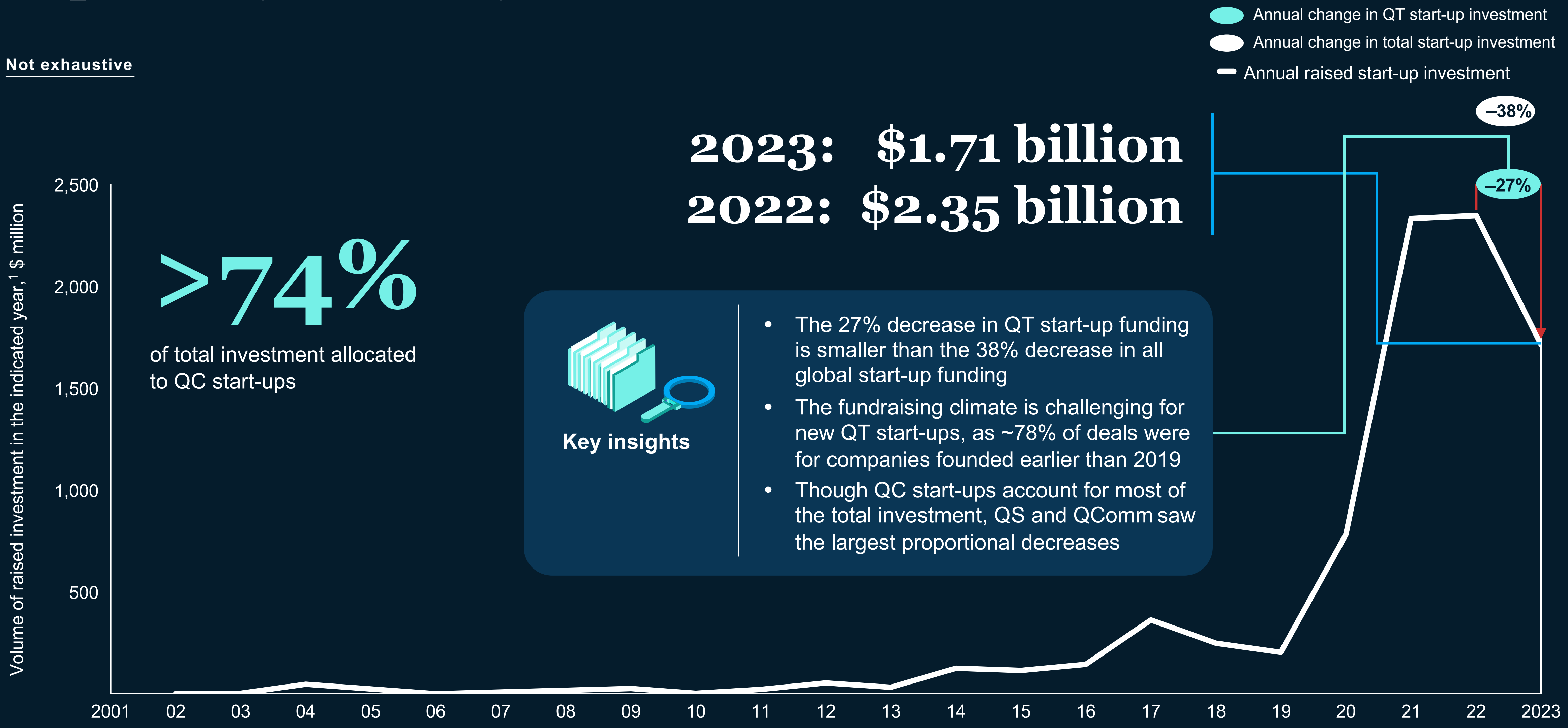
Contents



Quantum technology investment landscape

Total investments in quantum technology start-ups decreased by 27 percent year-over-year in 2023.

Not exhaustive



>74%

of total investment allocated to QC start-ups

Key insights

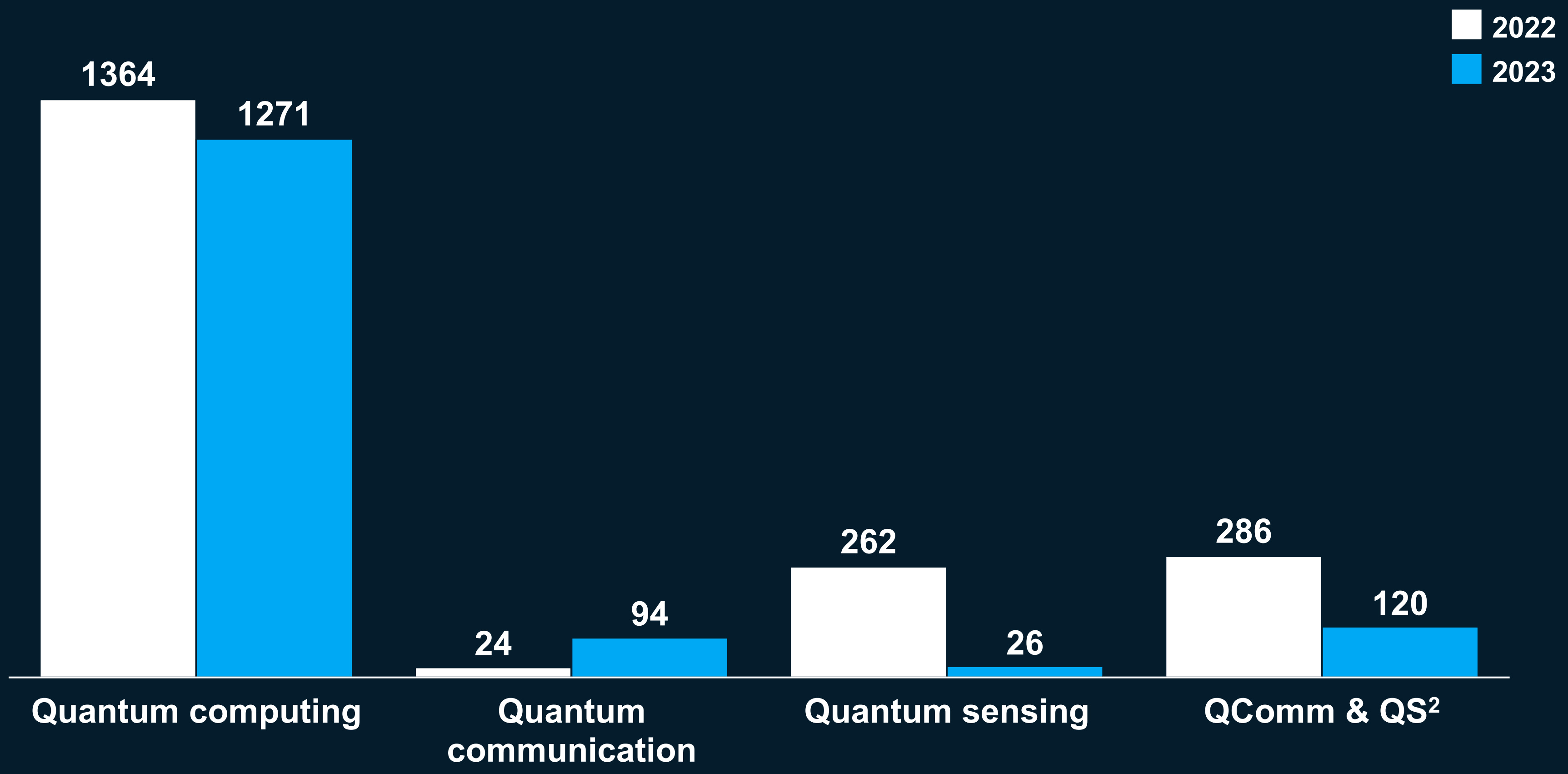
- The 27% decrease in QT start-up funding is smaller than the 38% decrease in all global start-up funding
- The fundraising climate is challenging for new QT start-ups, as ~78% of deals were for companies founded earlier than 2019
- Though QC start-ups account for most of the total investment, QS and QComm saw the largest proportional decreases

[1]Based on public investment data recorded in PitchBook; actual investment is likely higher.

Source: PitchBook

All quantum technologies received less investment in 2023, especially quantum sensing.

Capital invested on QC, QComm, and QS start-ups, 2022–2023,[1] $ million



Key insights

QS companies saw the largest decline in investment, while companies whose technologies are used for QS and QComm also saw a significant decrease

Pure-play companies in QComm increased in funding

QC companies had a modest decrease

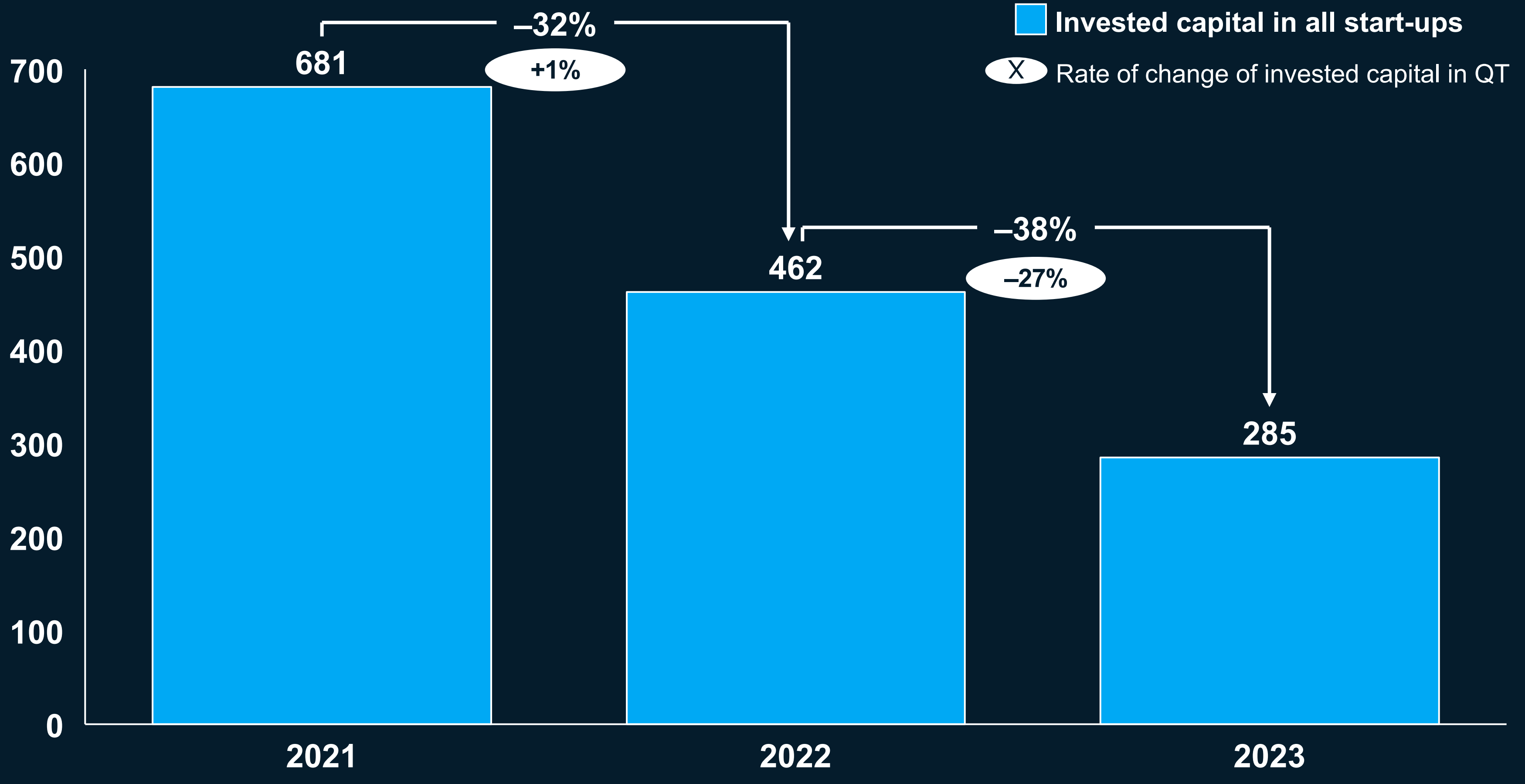
Note that funding from public sources for some defense applications of QT are not included in this analysis

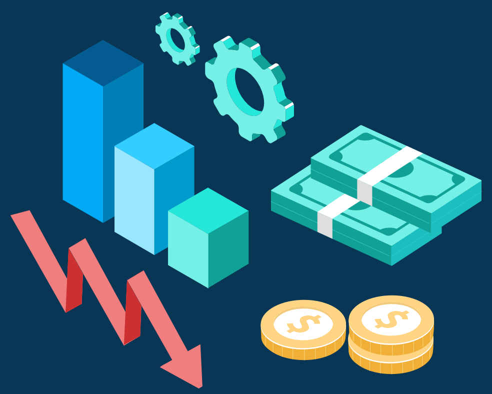
[1] Funding that is unspecified by any type of quantum technology (QC, QComm, QS) are excluded from the analysis, and information on activity in China is limited.
[2] Includes companies whose technologies focus on both quantum communication and quantum sensing.

Source: PitchBook

However, the decrease in QT investments is smaller than the 38 percent decline in overall global start-up funding in 2023.

Total capital invested into all start-ups globally, 2021–2023,[1] $ billion





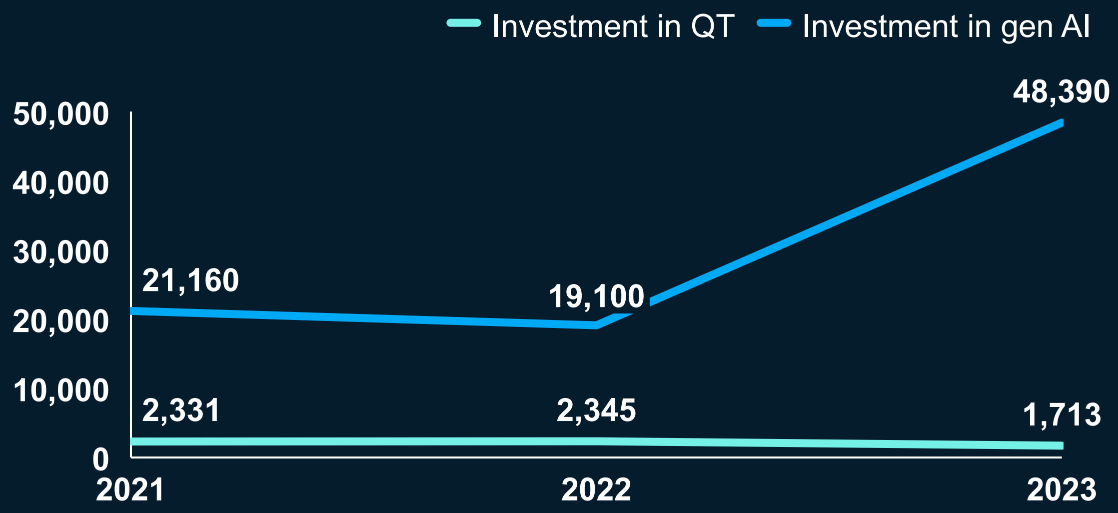
Slower investment into all start-ups continued in 2023 globally, likely due to inflation, high interest rates, and geopolitical uncertainty

[1]Based on public investment data recorded in PitchBook; actual investment is likely higher.

Source: Crunchbase; McKinsey analysis

Investments into QT decreased, while gen AI increased dramatically, but VC deal volumes of QT are comparable to that of AI a decade ago.

Total investments in QT and gen AI, 2021–2023,[1] $ million



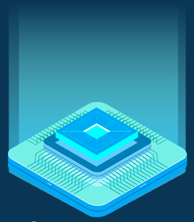
VC deals for QT vs AI, $ million

Technology: Quantum, AI
Total deal volume: Size of bubble

	2012	2017	2022
QT	107	417	2,078
3-year cumulative	321	1,037	5,613
AI	2,244	29,150	76,828
3-year cumulative	5,556	68,284	261,090

Factors driving decreases for QT and increases in gen AI investment

- Heavy shift in focus toward generative AI due to its near-term commercial potential
- QT (especially QC) is perceived as a long-term technology whose potential in various sectors is still being understood and evaluated
- Uncertainty in timeline for achieving significant commercial success in QT



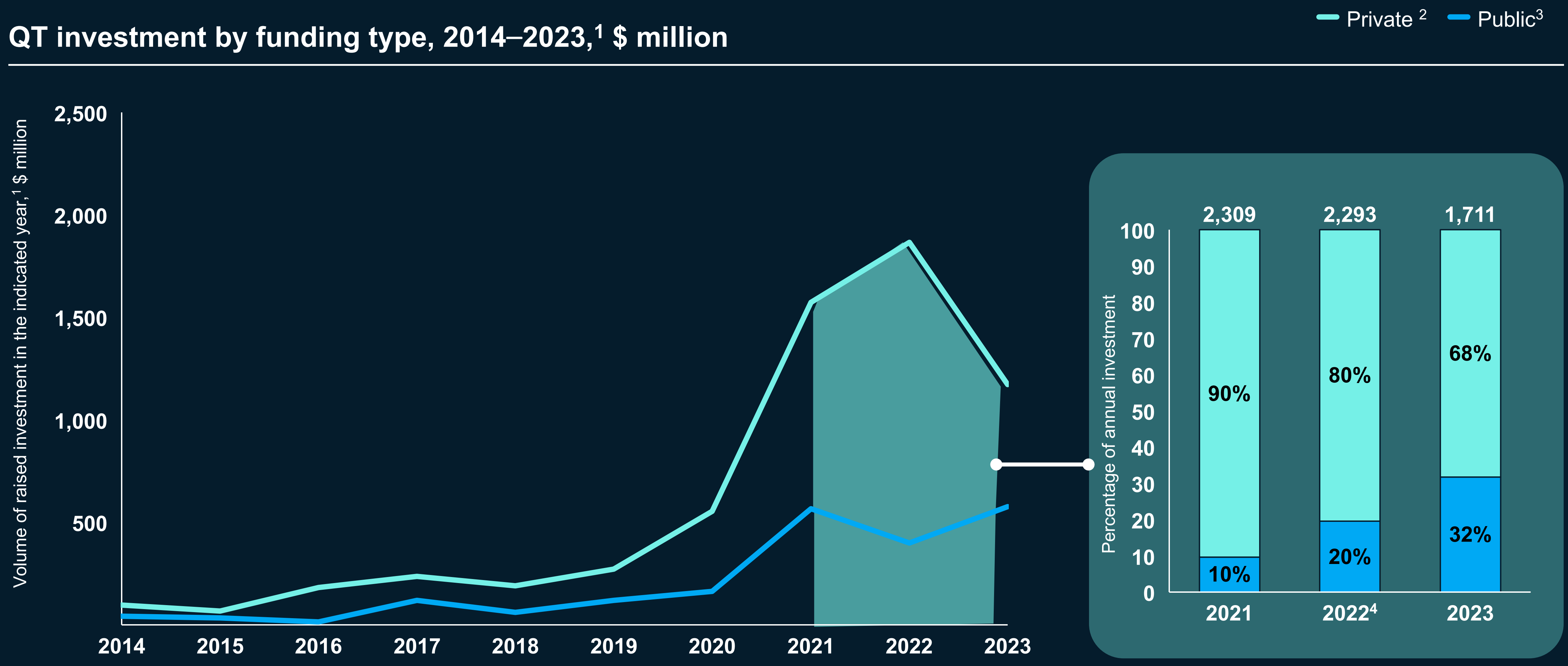
- **Funding for QT is comparable to that for AI a decade earlier** based on a pure comparison of deal volume
- **The 3-year cumulative deal volume for QT** is **already above that for AI** a decade ago, where VC funding for AI increased rapidly after 2017
- **However, requirements for QT development differ from that of AI for hardware (especially) and software**, which impacts the funding requirements and tech maturity timelines

[1]Based on public investment data recorded in PitchBook; actual investment is likely higher.

Source: PitchBook

The decrease in QT start-up investment is reflected only in private funding; public funding increased in 2023.

QT investment by funding type, 2014–2023,[1] $ million

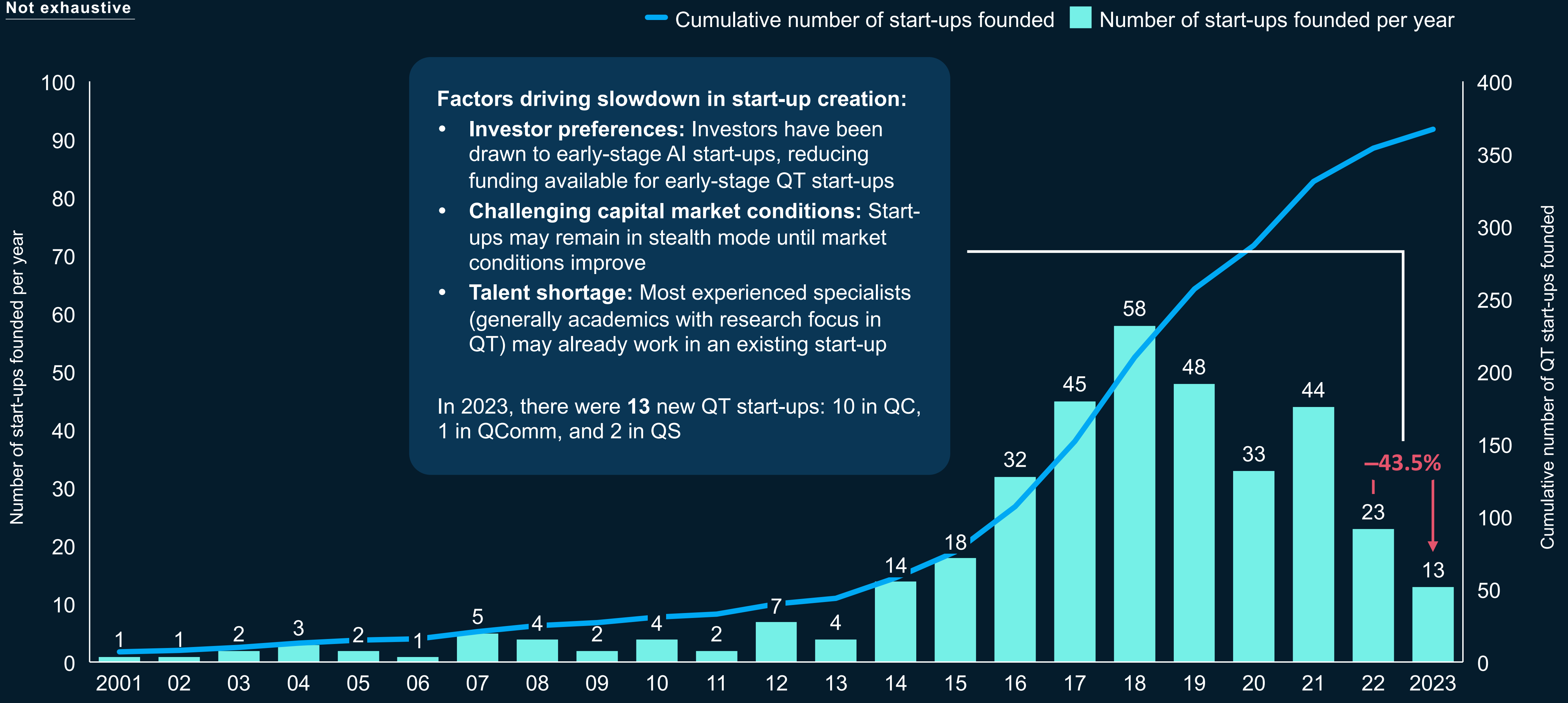


[1]Based on public investment data recorded in PitchBook; actual investment is likely higher.
[2]Includes investments from VC funds, hedge funds, corporates, angel investors, and accelerators.
[3]Includes investments from government, state, and public institutions.
[4]Excludes other uncategorized funding data.

Source: PitchBook

QT start-up creation continued to slow in 2023.

Not exhaustive



Factors driving slowdown in start-up creation:

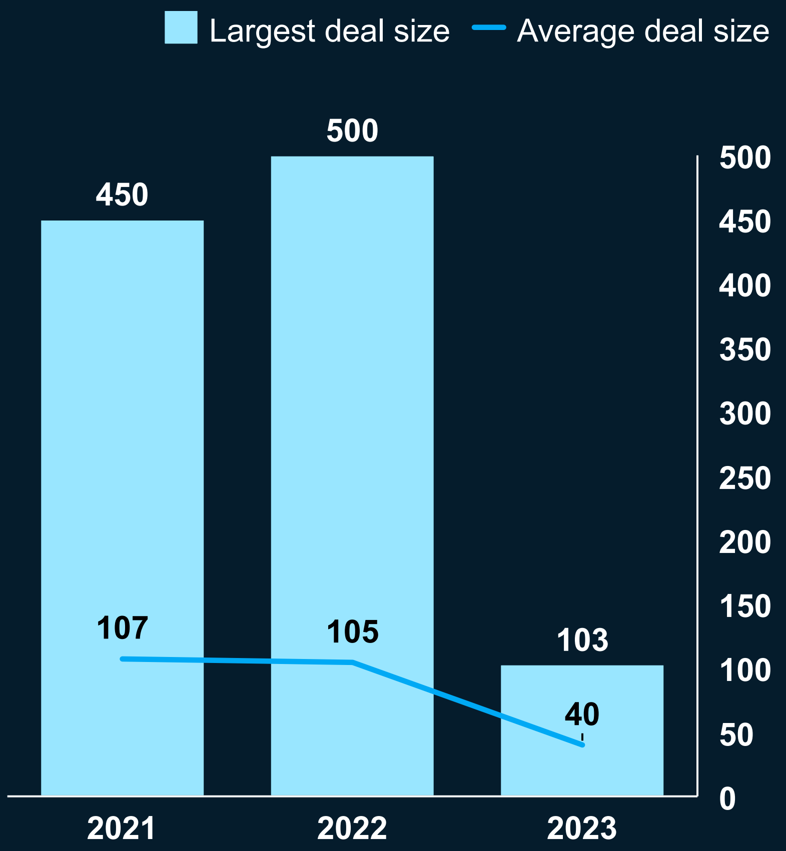
- **Investor preferences:** Investors have been drawn to early-stage AI start-ups, reducing funding available for early-stage QT start-ups
- **Challenging capital market conditions:** Start-ups may remain in stealth mode until market conditions improve
- **Talent shortage:** Most experienced specialists (generally academics with research focus in QT) may already work in an existing start-up

In 2023, there were **13** new QT start-ups: 10 in QC, 1 in QComm, and 2 in QS

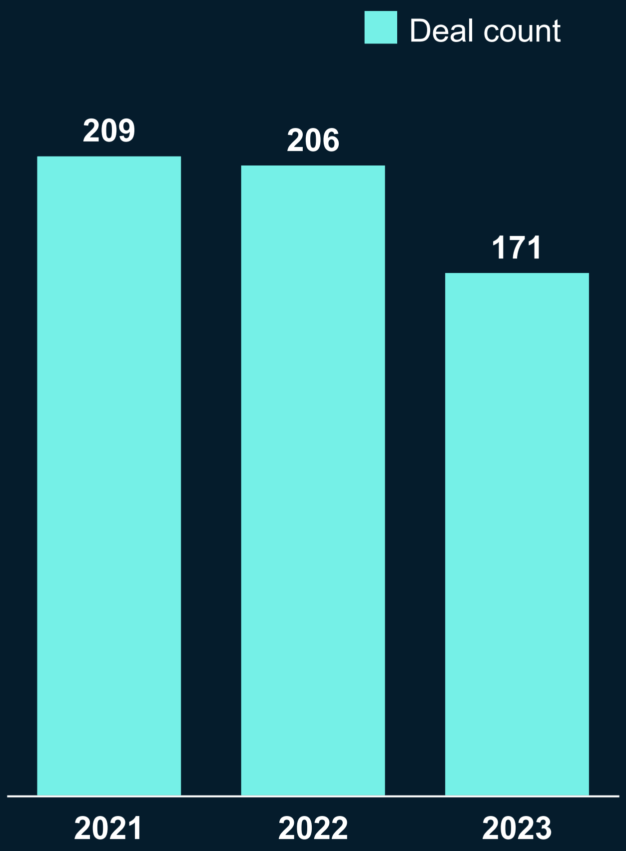
Source: Crunchbase; PitchBook

Deal sizes and counts also decreased significantly in 2023.

Change in deal size (top 20 deals), 2021–2023, $ million



Change in deal counts, 2021–2023



Factors affecting decreasing deal sizes

- **Higher interest rates** severely constrain funding environment (most funds were raised or invested in low-capital cost environments), with many start-ups also raising multiyear rounds
- **Popularity of gen AI** and corresponding shift in investment focus leading to limited available capital for QT
- **Consolidation and maturation** leading to shift from VC funding to corporate and government funding

Source: PitchBook

Only five out of the top ten deals in 2023 were valued at more than $50 million.

Top ten venture capital/private equity investments in QT start-ups in 2023, by deal size (descending)

Not exhaustive

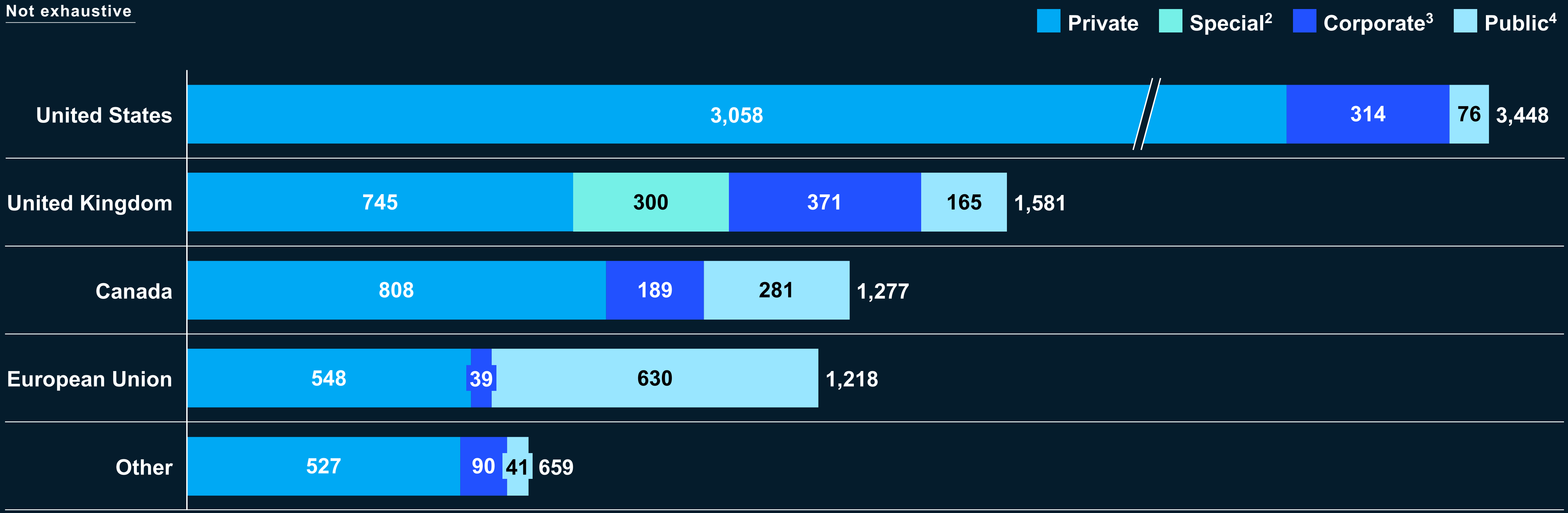
Quantum computing | Quantum communication | Quantum sensing

Company	Country	Tech	Segment	Deal size, $ million	Deal type
1 Pasqal	France	Quantum sensing, Quantum communication, Quantum computing	Hardware manufacturing	103	Series B
2 Photonic	Canada	Quantum computing	Hardware manufacturing	100	Series D
3 OQC	United Kingdom	Quantum communication, Quantum computing	Application software	100	Series B
4 Q-CTRL	Australia	Quantum computing	System software	52	Series B
5 Quantum Motion	United Kingdom	Quantum computing	Hardware manufacturing	51	Series B
6 Silicon Quantum Computing	Australia	Quantum computing	Hardware manufacturing	50	Series A
7 Xpanceo	United Arab Emirates	Quantum computing	Hardware manufacturing	40	Seed round
8 Quandela	France	Quantum sensing, Quantum communication, Quantum computing	Hardware manufacturing	39	Series A
9 Oxford Ionics	United Kingdom	Quantum computing	Hardware manufacturing	36	Series A
10 NVision Imaging Technologies	Germany	Quantum sensing	Application software	30	Series A

Source: Crunchbase; PitchBook

The majority of investment is in US companies, followed by the United Kingdom, Canada, and the European Union.

Total investment in QT start-ups by location and primary investor type, 2001–2023, $ million[1]

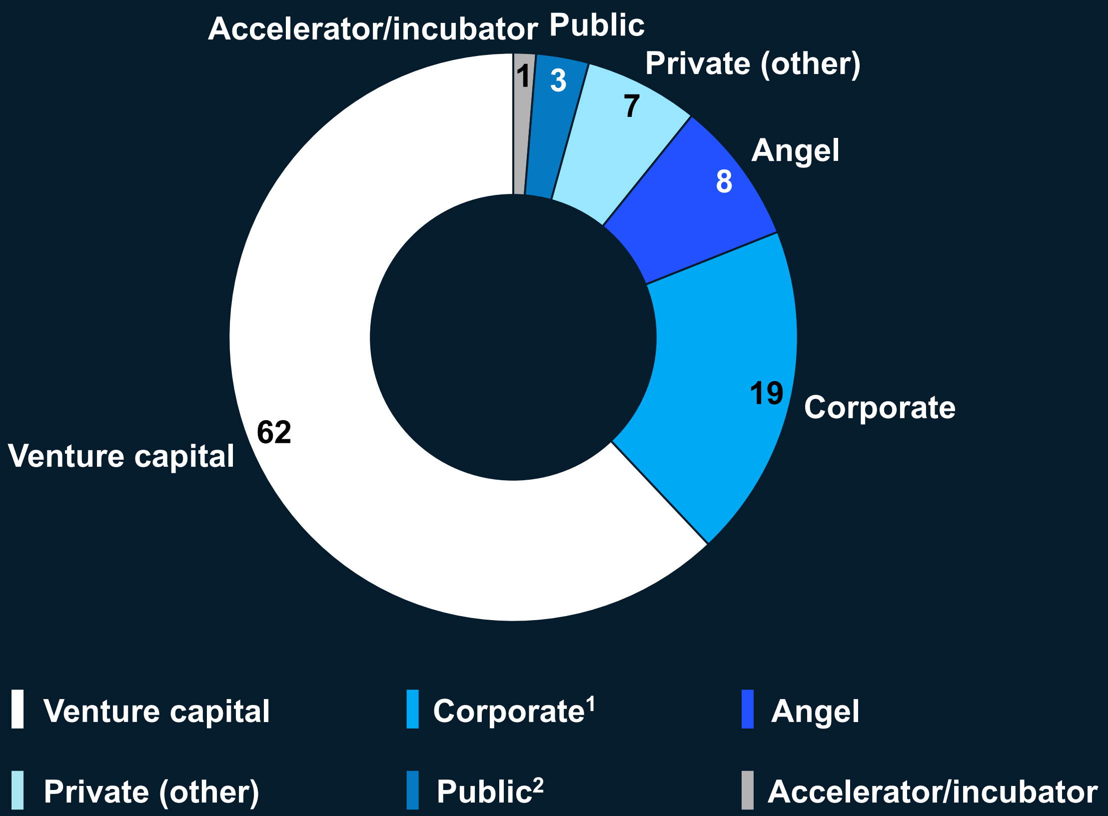


[1]Based on PitchBook data. Actual investment volume in QTs is likely higher; data availability on start-up investment in China is limited.
[2]Includes SPACs (eg, Rigetti Computing) and other special deal types (eg, Honeywell's investment of $300 million in Quantinuum).
[3]Includes investments from corporations and corporate venture capital in external start-ups; excludes corporate investments in internal QT programs.
[4]Includes investments by governments, sovereign wealth funds, and universities.

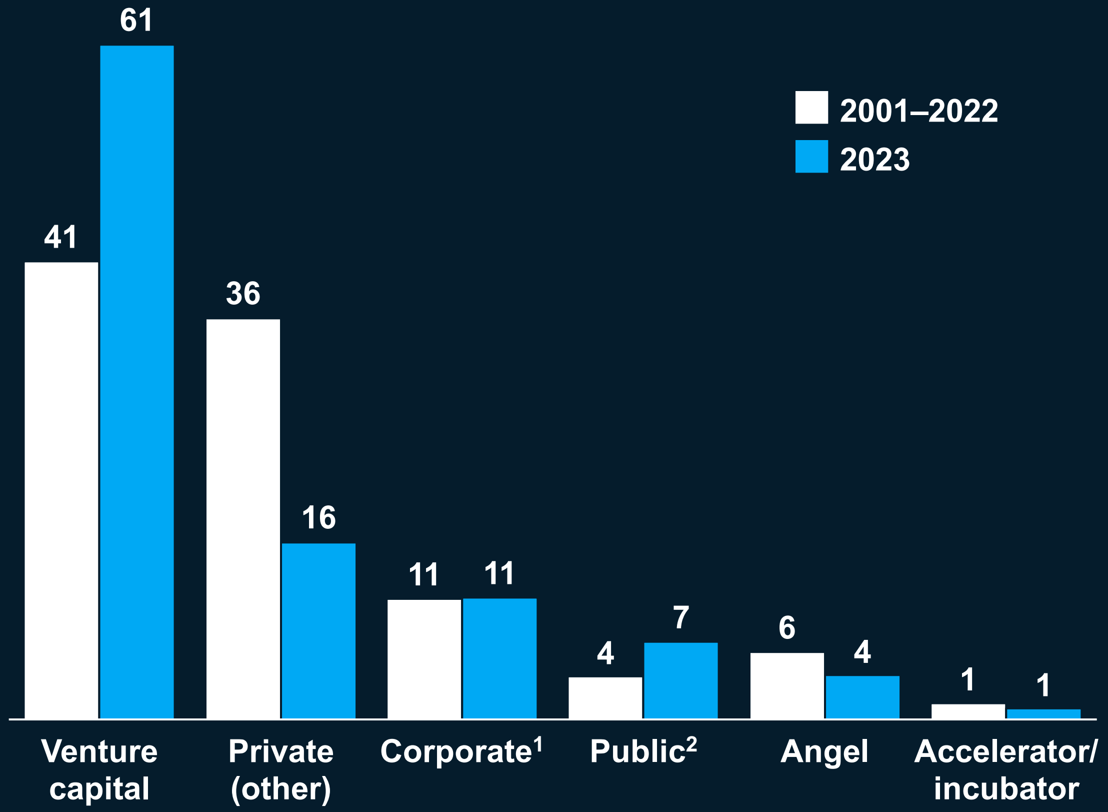
Source: ICV Thinktank; IT橘子(IT Orange); PitchBook

Venture capital and other private capital make up nearly 80 percent of QT inflows.

Split of QT investments, by investor type, 2001–2023 (% of total investment value)



Change in QT investments, by investor type, 2001–2022 vs 2023 (% of total investment value)

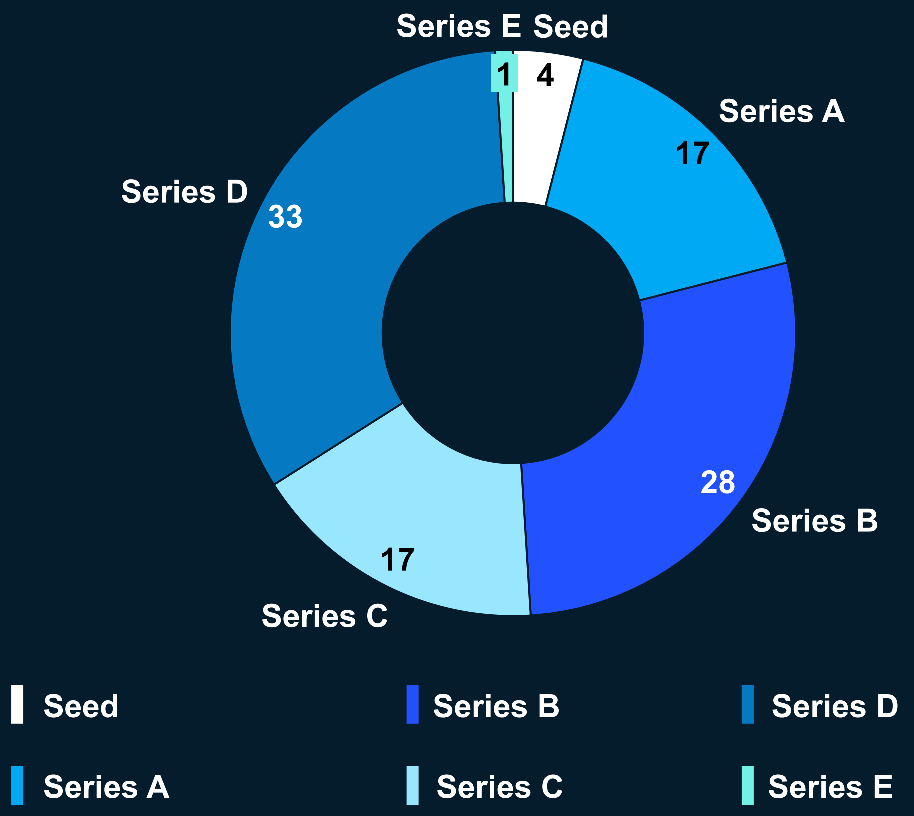


[1]Includes corporations, corporate venture capital, venture-capital-backed companies, and private-equity-backed companies investing in an external start-up; does not include corporations investing in internal QT programs.
[2]Includes governments, sovereign wealth funds, and universities.

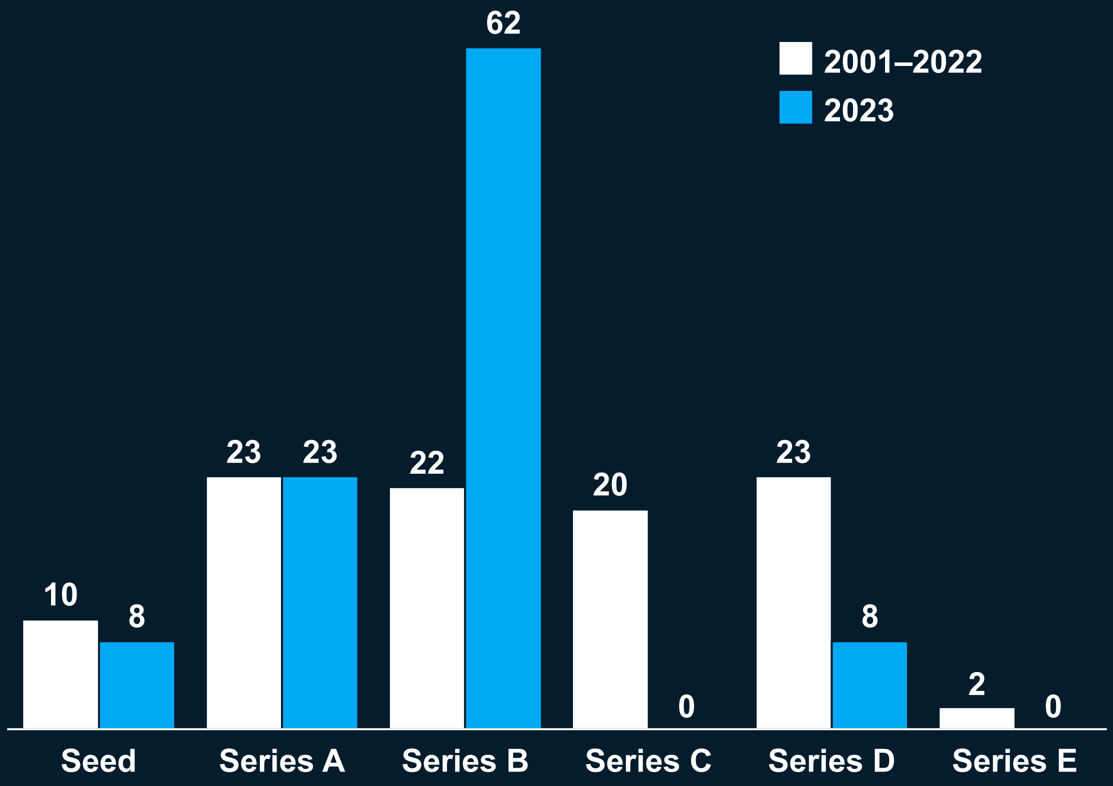
Source: PitchBook

The majority of investments so far have gone toward scaling up established start-ups.

Split of VC investments, by deal type, 2001–2023
(% of total investment value)



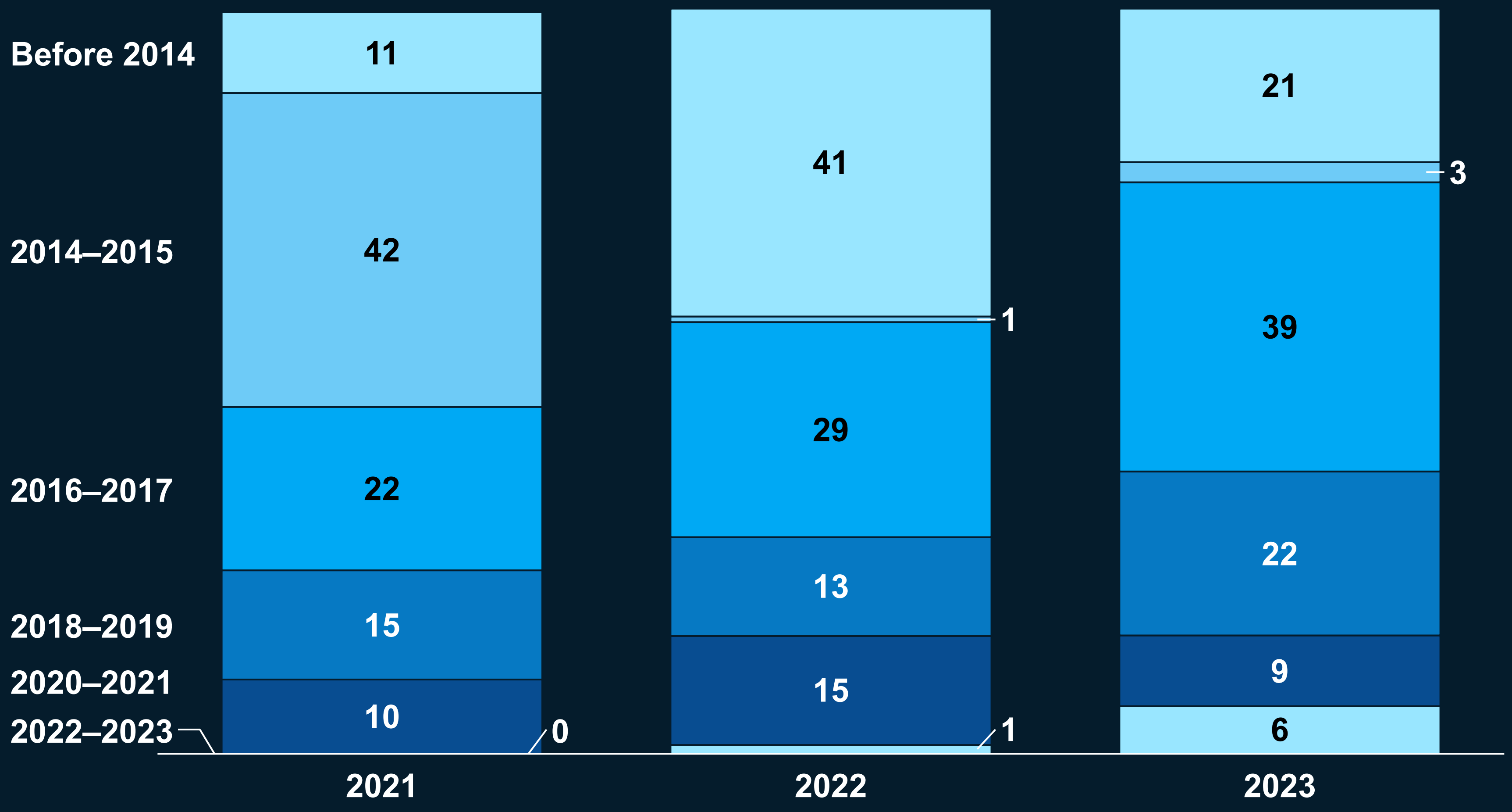
Split of investments, by investment type, 2001–2022 vs 2023
(% of total investment value for each period)



Source: PitchBook

The majority of annual funding has gone to more mature start-ups that are at least five years old.

QT investment split based on founding years of start-ups in 2021–2023,[1] %



Key insights

- New start-ups may find attracting funding challenging, as more than half of investments each year go to companies founded more than five years ago
- Private investors may prefer to limit risks by avoiding uncertain, new technology and continue to invest in older, more established start-ups

[1]There is limited information available on activity in China.

A number of countries announced significant additional public funding for QT development, totaling ~$10 billion in 2023.

National and regional funding announcements

Announced in 2023 | Announced before 2023

Not exhaustive

The **Australian** government released the National Quantum Strategy in 2023, with an investment plan of $60 million.

The **Canadian** government launched a National Quantum Strategy (NQS), with an announcement of a $360 million investment in 2023.

China has boosted government funding for quantum research and development to over $15 billion, with applications in security, defense, and AI.

France has committed to establishing a leading position in the international quantum technology race, with a $1.3 billion investment announced in 2021.

The **German** government announced an investment of $2.25 billion into quantum technologies, with a goal to develop a universal quantum computer expected to have around 100 qubits by 2026 and 500 qubits in the near term.

The government of **India** announced the National Quantum Mission (NQM), which aims to seed, nurture, and scale up scientific and industrial R&D and create a vibrant and innovative ecosystem in quantum technology, with $730 million in funding.

The **Japanese** government announced $32 million to support the expansion of shared quantum computing through a cloud platform to expedite use-case development in sectors such as automotive, chemical, finance, etc. This comes after the $1.8 billion announced in 2022.

The **Korean** government plans to invest $2.3 billion in quantum science and technology by 2035, with a goal to become a leading player in quantum technology.

The **Netherlands'** National Growth Fund has allocated Quantum Delta NL funding of $65 million in 2023. The organization is a main driver in the Netherlands' national ecosystem for quantum innovation.

The **Russian** government announced in 2021 that it would invest $790 million in quantum computing research over the next five years. This investment is part of a larger effort by Russia to develop its technological capabilities.

The **United Kingdom's** National Quantum Strategy introduced new strategic goals for the next ten years, including market growth stimulation, research, and talent, with additional investment worth $3.1 billion.

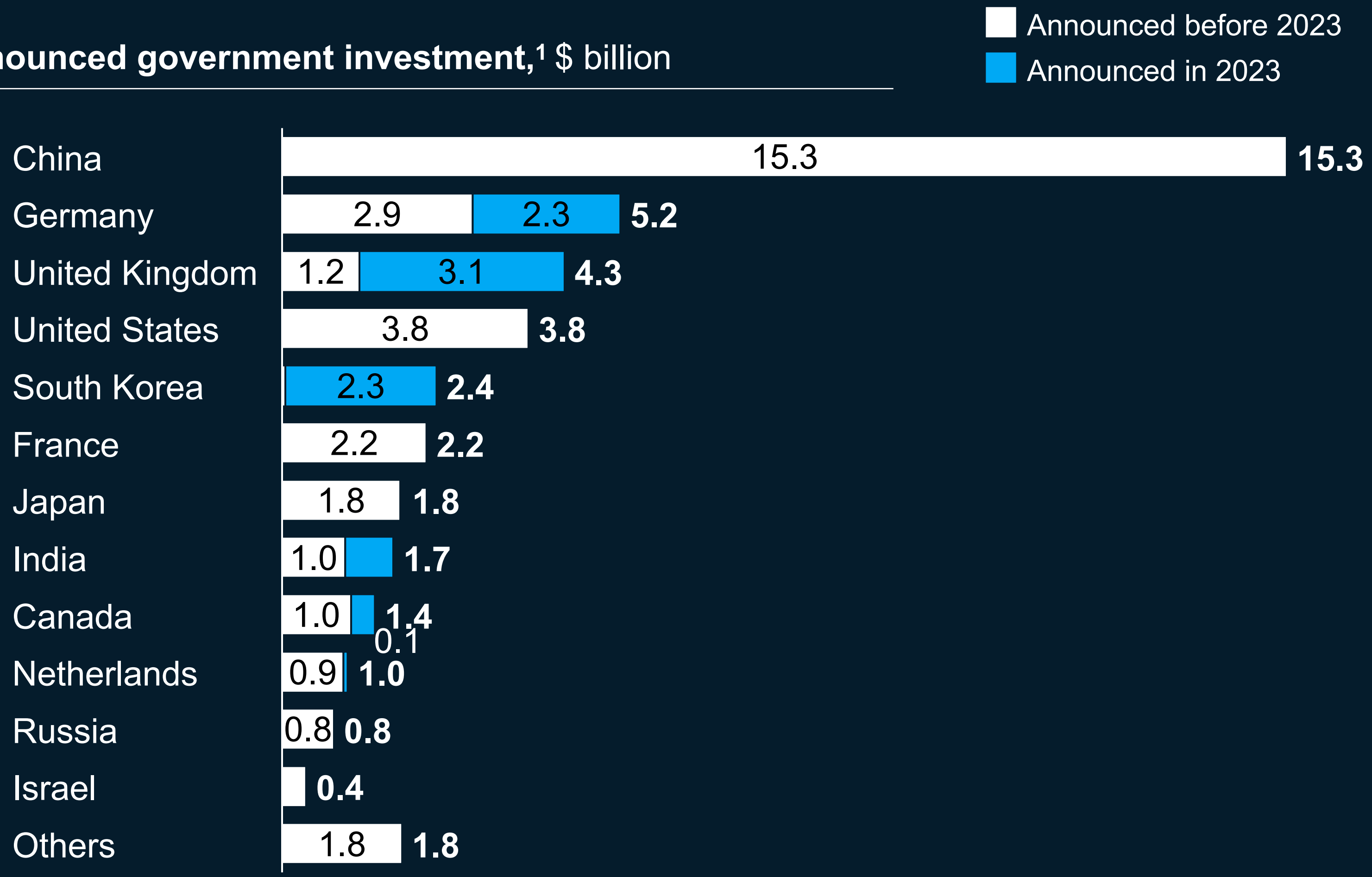
The **United States** announced in 2018 the National Quantum Initiative, which provides $1.2 billion over five years for quantum technology development.

Source: National and regional government press releases

Global public investments in QT reached $42 billion in 2023.

Not exhaustive

Announced government investment,[1] $ billion



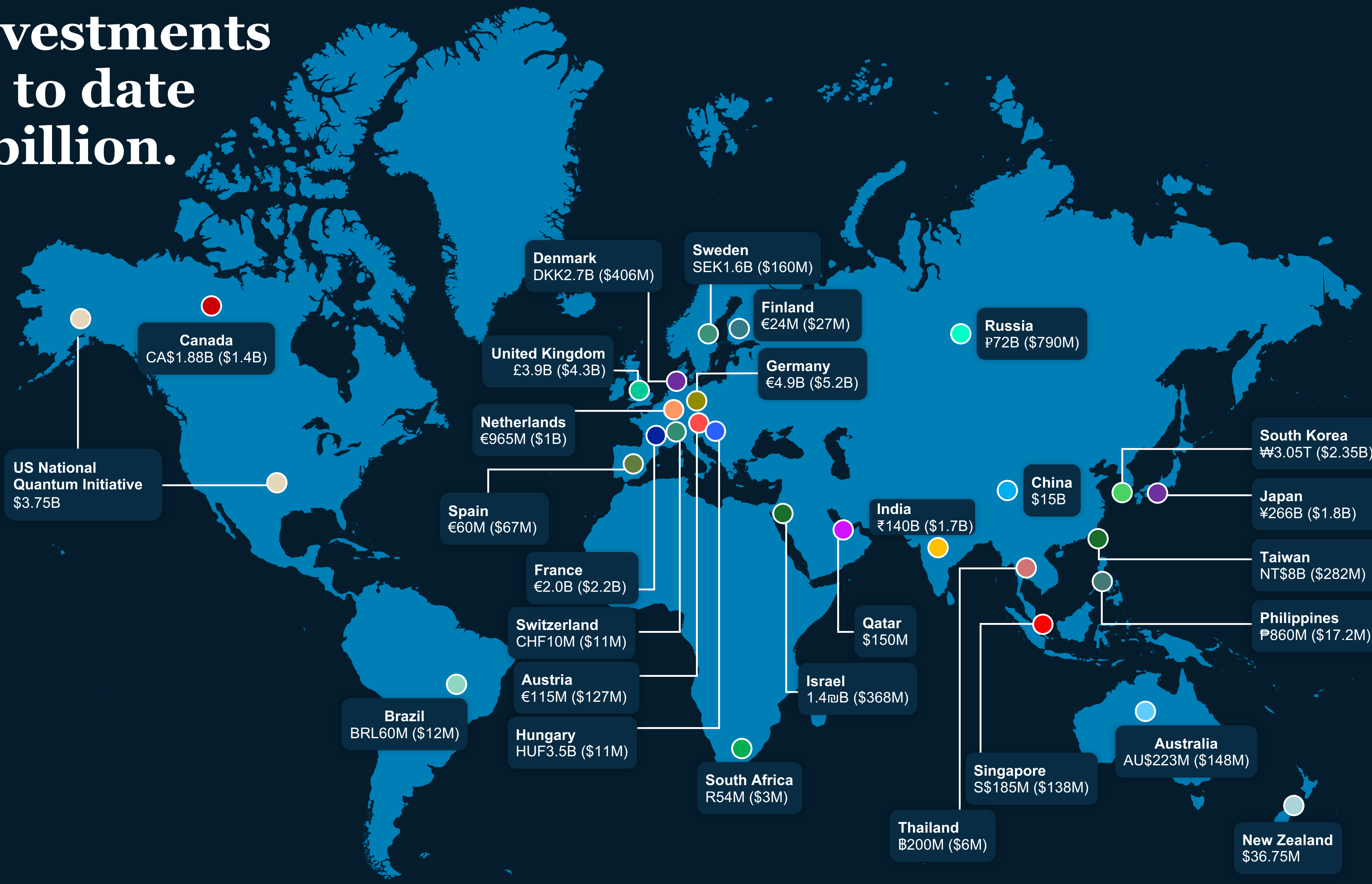
Key insights

- While China and the United States previously dominated QT public investment, new announcements from Germany, the United Kingdom, South Korea, and India created a more diverse global QT development landscape in 2023
- While all 2023 announcements nearly doubled public funding for each country, South Korea and the United Kingdom significantly increased their funding levels
- Many public funding announcements included plans to attract private investment as part of overall program goals

[1]Total historic announced investment; timelines for investment vary by country.

Source: McKinsey analysis

National investments announced to date total ~$42 billion.



Note: The boundaries and names shown on maps do not imply official endorsement or acceptance by McKinsey & Company.

Internal market size and value at stake

What are internal market size and value at stake?

Internal market size

Market size of quantum technologies infrastructure, hardware, software, and services (ie, entire tech stack for quantum technologies)

QT tech stacks include:

- Physical components
- Assembled hardware
- Embedded and application software
- Networking (eg, cloud infrastructure)

Value at stake

Economic value from impact of quantum technologies on non-QT industries along the entire value chain

Example industries:

- Finance
- Pharmaceuticals
- Energy and materials

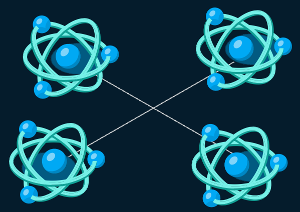
Example value chain components:

- Material design (eg, simulation)
- Manufacturing (eg, process optimization)

The total internal market size for QT could reach an estimated $173 billion by 2040.

Growth rate[1] ■ Conservative ■ Optimistic

Quantum technology market-size scenarios in 2035 and 2040



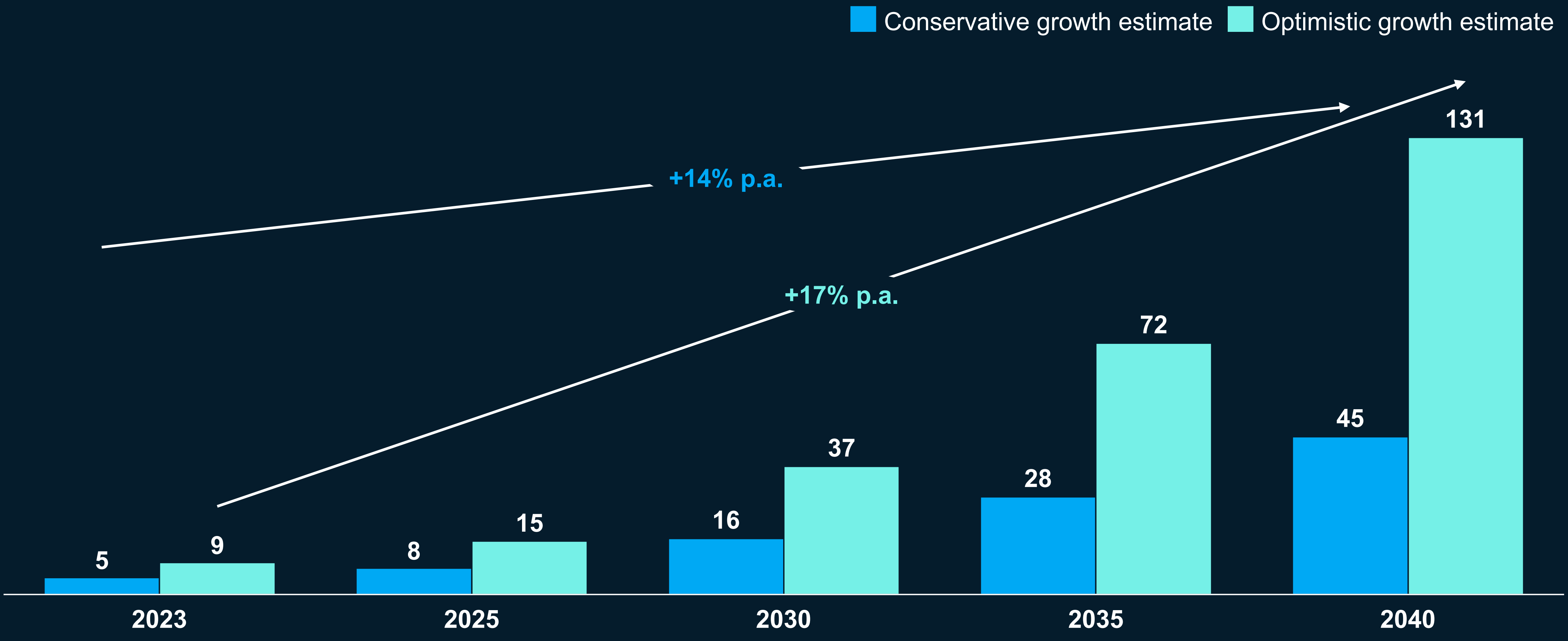
	Quantum computing		Quantum communication		Quantum sensing	
	Conservative	Optimistic	Conservative	Optimistic	Conservative	Optimistic
2035	$28B	$72B	$11B	$15B	$0.5B	$2.7B
2040	$45B	$131B	$24B	$36B	$1B	$6B

[1]Based on existing development road maps and assumed adoption curves per technology.

Source: McKinsey analysis

The quantum computing market is expected to reach $28B–$72B by 2035 and $45B–$131B by 2040.

Expected market size in each scenario,[1] $ billion



[1]Market projection follows an adoption curve for quantum computing assuming a timeline to quantum advantage based on understanding of current QT and projected total high-performance-computing market sizes.

Source: Etale data, market data, expert interviews, and McKinsey analysis

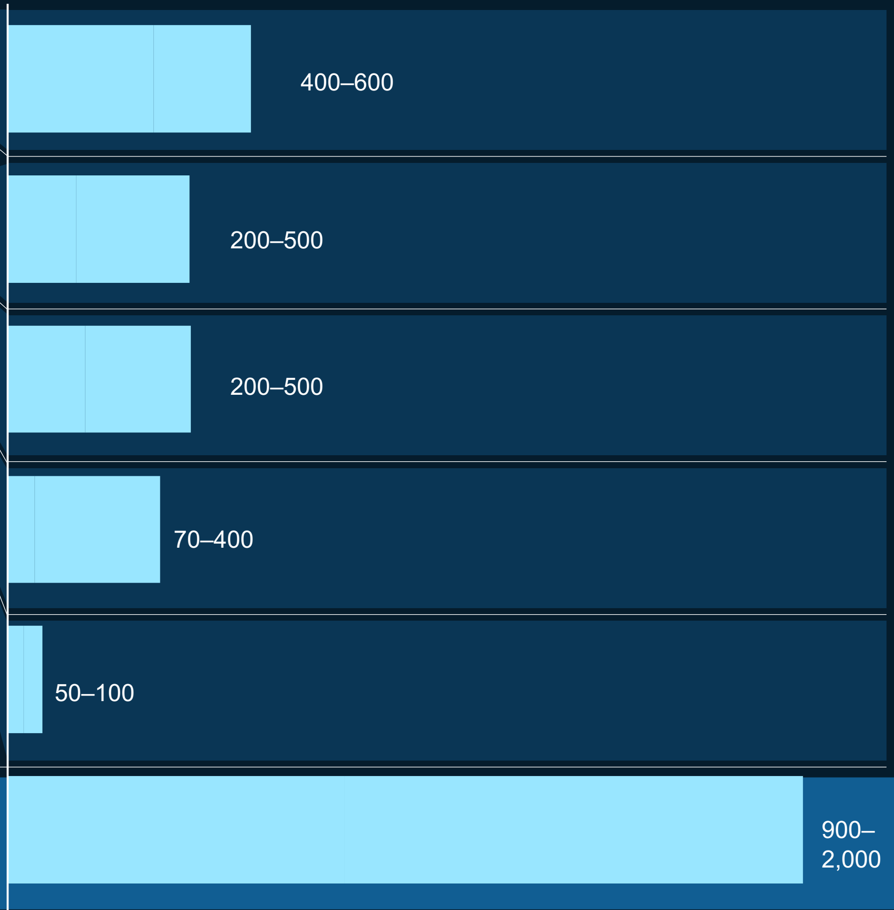
QC presents a $1T to $2T opportunity, with rapid acceleration expected in the coming five to ten years.

Preliminary

Deep dive next | Economic value: + Low | ++ Medium | +++ High

Industry	Key segment for QC	Economic value[1] ~2025–2030	Economic value[1] ~2030–2035	2035 market size, $ trillion
Financial industry[1]	Financial services	++	+++	14.1
Global energy & materials	Oil and gas	+	++	
	Sustainable energy[2]	+	+++	
	Chemicals	++	+++	6.1
Travel, transport, & logistics	Travel, transport, and logistics	+	+++	14.1
Pharmaceuticals & medical products	Pharmaceuticals	++	+++	3.1
Advanced industries	Automotive	+	++	8.3
	Aerospace and defense	+	++	
	Advanced electronics	+	++	
	Semiconductors	+	++	
Insurance	Insurance	+	++	
Telecommunications, media, & technology	Telecommunications	+	++	
	Media	+	+	

Value at stake with incremental impact of QC by 2035, $ billion



Total

[1]Quantum computing technologies and industry is immature and has high uncertainty for viability and value of use cases. Business-value estimates are preliminary and intended to guide research toward high-value-potential areas, not as definitive projections for business value. Insurance is not included.
[2]Sustainable energy market is expected to grow rapidly from 2022–2035; however, the 2035 market size is influenced by numerous factors and challenging to predict.

Source: McKinsey analysis; Oxford Economics

Technological breakthroughs

Groundbreaking milestones were achieved by key players in 2023, keeping the QC ecosystem on track in the race for logical qubits

Not exhaustive

Quantum computing | Quantum communication | Quantum sensing | **Theme**: Logical qubits | Error detection and correction

QT	Innovation	How it works	What it means
Quantum computing (Logical qubits)	Microsoft and Quantinuum demonstrate the most reliable logical qubits on record, with an error rate 800 times better than physical qubits. **Apr 2024**	Microsoft's qubit-virtualization system and Quantinuum's ion-trap hardware used to run 14,000+ experiments without a single error. Quantinuum's ion-trap quantum processors achieve an exceptional two-qubit gate fidelity of 99.9% and quantum volume (QV) of 1,048,576.	This moves us beyond the current NISQ[1] era toward resilient quantum computing, with logical qubits protected against noise and sustaining longer computation.
Quantum computing (Error detection and correction)	IBM demonstrated 12 logical qubits preserved for nearly 1 million syndrome cycles using 288 physical qubits. **Mar 2024**	IBM's so-called gross code requires 144 qubits to store data and another 144 qubits to check for errors, using 288 qubits. It stores 12 logical qubits well enough that fewer than 12 errors can be detected.	Prior surface codes would require nearly 3,000 physical qubits for the same thing.
Quantum computing (Error detection and correction)	Amazon (AWS) demonstrated a new approach called "erasure error detection and correction." **Mar 2024**	A new type of qubit that converts the majority of errors into a special class known as "erasure errors" based on superconducting transmons. These errors can be detected and fixed much more efficiently than standard quantum errors.	Erasure error detection and correction, under the right circumstances, can lead to significant reductions in error-correction overhead.
Quantum communication	Chinese scientists introduced a technique that they say could help secure Web 3.0. **Feb 2024**	Long-distance free-space quantum secure direct communication (LF QSDC) enhances data security by enabling direct transmission of encrypted messages without the need for key exchange, unlike QKD[2] and classical encryption.	Advancements in QSDC protocol for quantum cryptography offers a step on the path toward a secure Web 3.0.
Quantum sensing	Researchers at MIT developed a new technique to further improve sensitivity of center–based quantum sensor technology. **Feb 2024**	Quantum sensor technology based on nitrogen-vacancy (NV) center uses microscopic defects inside diamonds to create "qubits." The NV center is detected and excited using laser light and controlled with microwave pulses. MIT's spin echo double resonance (SEDOR) approach uses a protocol of microwave pulses to identify and extend that control to additional defects that can't be seen with a laser, called dark spins.	This is a promising direction in NV center–based quantum sensing, which is currently a leading area of research in quantum sensing.

[1]Noisy intermediate-scale quantum.
[2]Quantum key distribution, a method of distributing quantum-safe encryption keys between parties.

Source: Company press releases

QComm and QS also made promising advancements in research and development recently.

Not exhaustive

Quantum computing | Quantum communication | Quantum sensing

Theme | Logical qubits | Error detection and correction

QT	Innovation	How it works	What it means
	Alice & Bob demonstrated 100 highly reliable logical qubits (with a 10^-8 error rate) using just 1,500 cat qubits. **Jan 2024**	Cat qubits, innovative qubit topology protecting against device-based noise, prevent decoherence without extracting information based on superconducting qubits. Combined with the LDPC[2] error-correction codes to further reduce resources needed for error correction.	Reducing physical qubits needed dramatically (eg, Shor's algorithm can be run with under 100,000 cat qubits vs 20 million qubit requirement).
	LG Electronics researchers developed a new protocol for quantum secure communication. **Jan 2024**	The new protocol introduced by LG Electronics proposes a high-dimensional, single-photon-based quantum secure direct communication (QSDC) protocol that does not require key exchange but also further overcomes limitations of current standard for QSDC DL04 protocol.	Enhances both the security and the transmission rate of quantum communication systems, overcoming some of the technical limitations.
	QuEra, Harvard, MIT, and NIST execute complex, error-corrected quantum algorithms on 48 logical qubits; achieve 99.5% two-qubit gate fidelity on 60 neutral atom qubits. **Dec 2024**	The researchers successfully executed large-scale algorithms on an error-corrected advanced neutral-atoms-based quantum computer. Creation and entanglement of the largest logical qubits at the time, demonstrating a code distance of 7 including construction of 40 medium-sized error-correcting codes by controlling 280 physical qubits.	A significant leap in quantum computing and sets the stage for developing truly scalable and fault-tolerant quantum computers.
	Scientists in China and Russia demonstrated the longest quantum communication so far, at over 3,800 kilometres. **Dec 2023**	This was made possible via an optical link with China's quantum satellite Mozi. The link connected a ground station near Moscow, Russia, to one in Urumqi, western Xinjiang region in China, enabling a secure transmission of two images encrypted with quantum keys.	As reported by South China Morning Post, BRICS[3] countries' successful collaboration indicates a strong strategic focus on QComm.
	Adtran and Orange demonstrated transmission of QKD[1]-secured data across 184km utilizing 400G technology. **Oct 2023**	The trial showcased a 400Gbit/s transmission of a QKD-secured 100Gbit/s data stream over 184km, using Adtran networking device and Toshiba's QKD systems, combining classical cryptography with QKD for dual-layer security.	Lab trials like these show the role of partnerships in advancing the design and implementation of QKD and PQC.[4]

[1]QKD = quantum key distribution.
[2]Low-density parity-check code, also known as sparse quantum code.
[3]BRICS = Brazil, Russia, India, China, and South Africa.
[4]PQC = post-quantum cryptography.

Source: Company press releases

Global research and IP landscape

The United States and Japan lead individual countries in patents granted, but EU countries outpace them in total.

QT patents granted, by HQ location, 2000–2023

Preliminary

	Total QT	QC	QComm	QS
United States	15,927	10,716	4,899	312
Japan	8,601	7,597	906	98
Germany	7,040	6,792	198	50
China	6,793	4,948	1,805	40
France	6,696	6,379	307	10
Switzerland	1,844	1,691	147	6
Great Britain	1,693	1,208	440	45
South Korea	1,635	1,342	272	21
Canada	1,480	866	566	48
Italy	1,293	1,215	64	14

The United States (37%) and Japan (20%) lead in share of global patents granted across all quantum technologies

The European Union accounts for 44% of the total patents granted in QT

China is now second in QComm patents, reflecting recent progress in that area

Source: Patsnap retrieved Jan 2024

The United States and China lead in patent requests filed, at about half of applications filed globally.

QT patent applications, by HQ location, 2000–2023

Preliminary

	Total QT	QC	QComm	QS
United States	30,099	18,263	10,918	918
China	28,593	23,667	4,678	248
Japan	13,689	11,861	1,642	186
France	8,094	7,513	555	26
Germany	5,935	5,111	699	125
Great Britain	3,516	1,960	1,426	130
Canada	3,123	1,723	1,304	96
South Korea	2,371	1,860	489	22
Switzerland	1,952	1,631	288	33
Netherlands	1,494	1,289	185	20

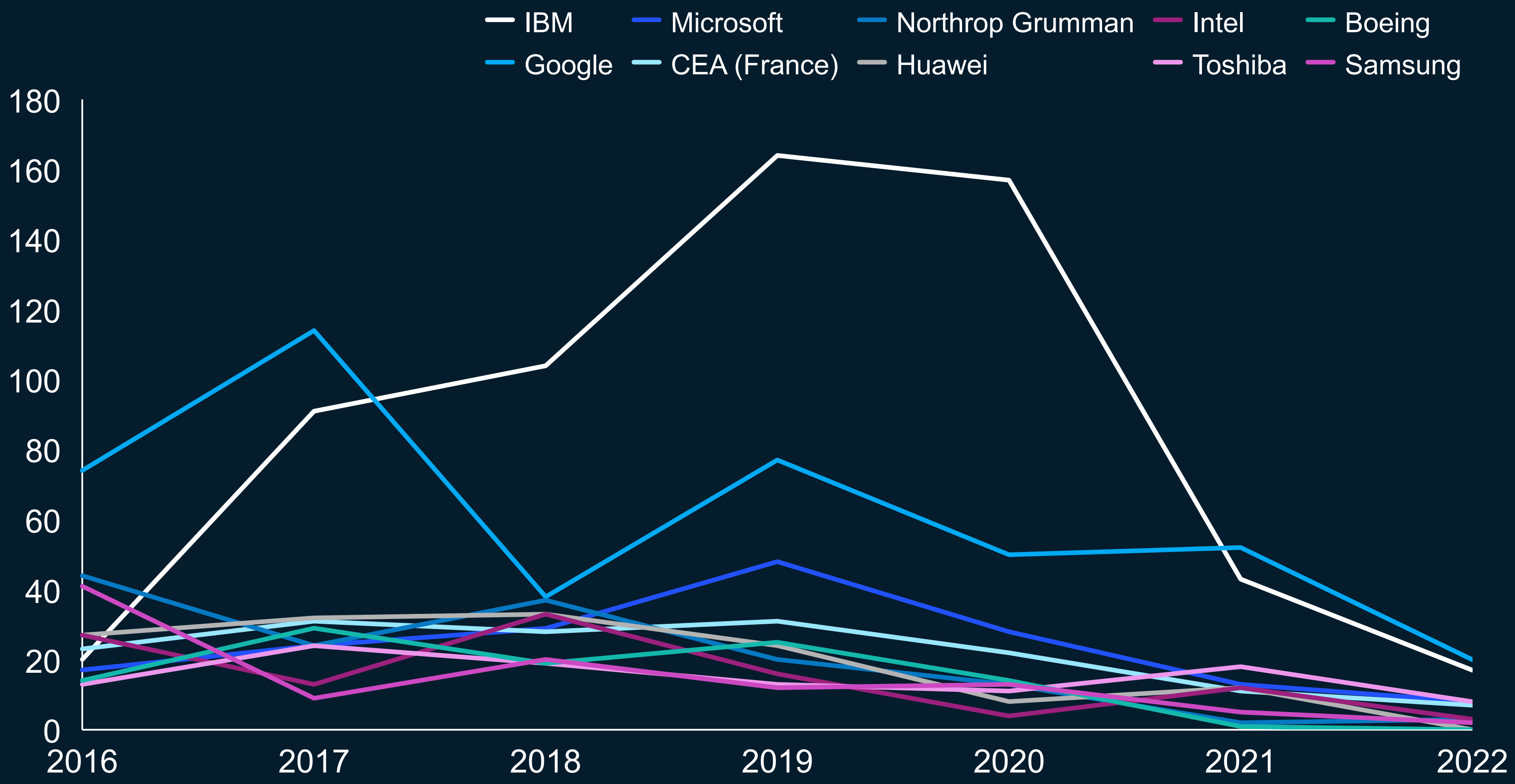
US and Chinese companies lead global QT patent applications, filing ~50% of total applications; EU companies comprise ~20% of requests

US companies lead significantly in number of QComm and QS patent applications; Chinese companies lead in number of QC applications

Source: Patsnap retrieved Jan 2024

Granted patents decreased for top players in 2021 and 2022.

Annual granted patents for top 10 companies[1] from 2016 to 2022



Insights

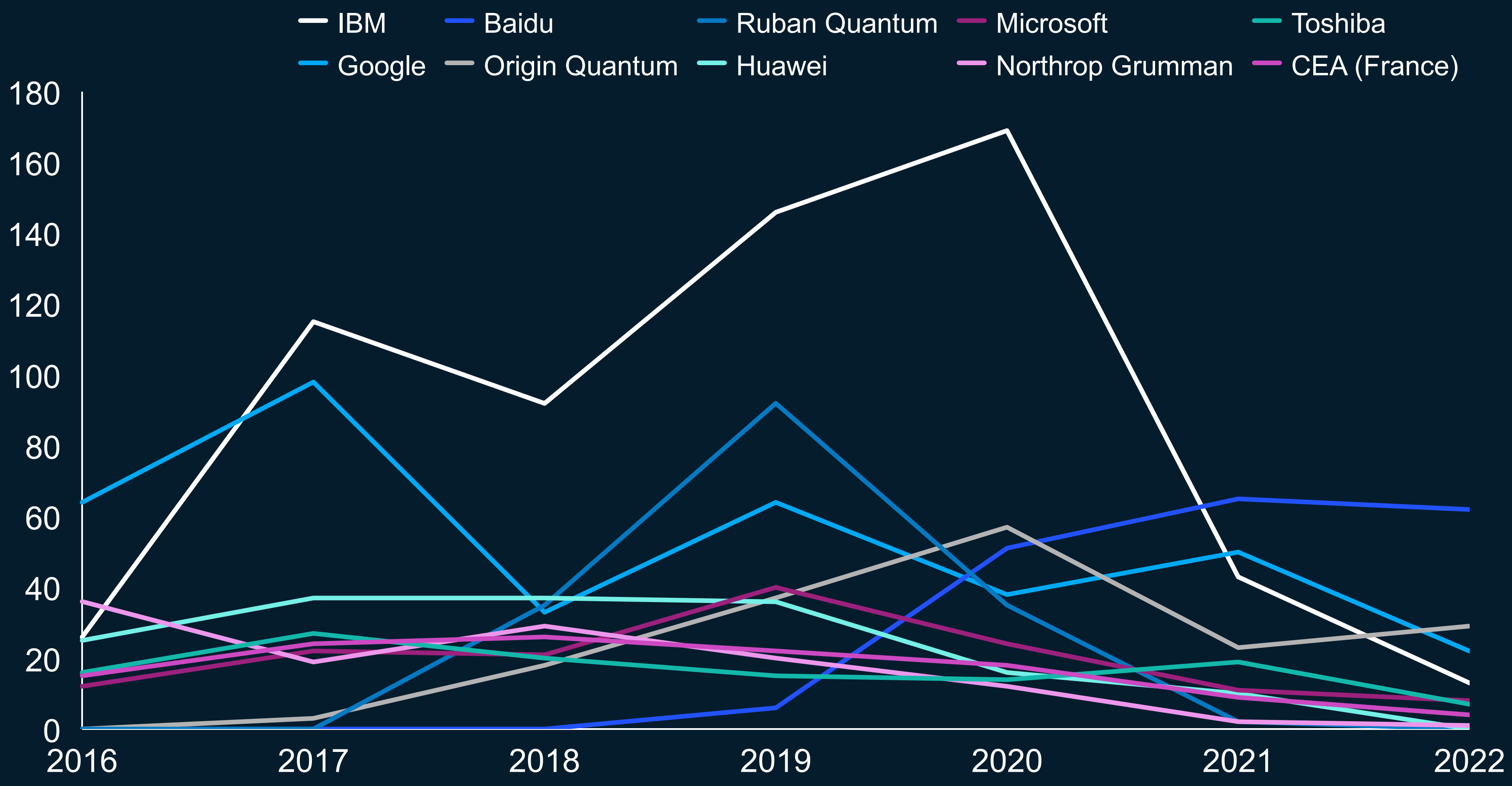
- Granted patents for QT decreased for the top ten players worldwide in all technology sectors, following a slowdown in private investments in QT
- IBM experienced the largest decrease in granted patents from a peak in 2019

[1]Companies ranked by cumulative number of patent applications.

Source: IP analytics; Patsnap retrieved Jan 2024

Patent applications decreased for the top ten companies in recent years, but at varied rates and timelines.

Annual filed patent applications for top 10[1] companies from 2016 to 2022



Insights

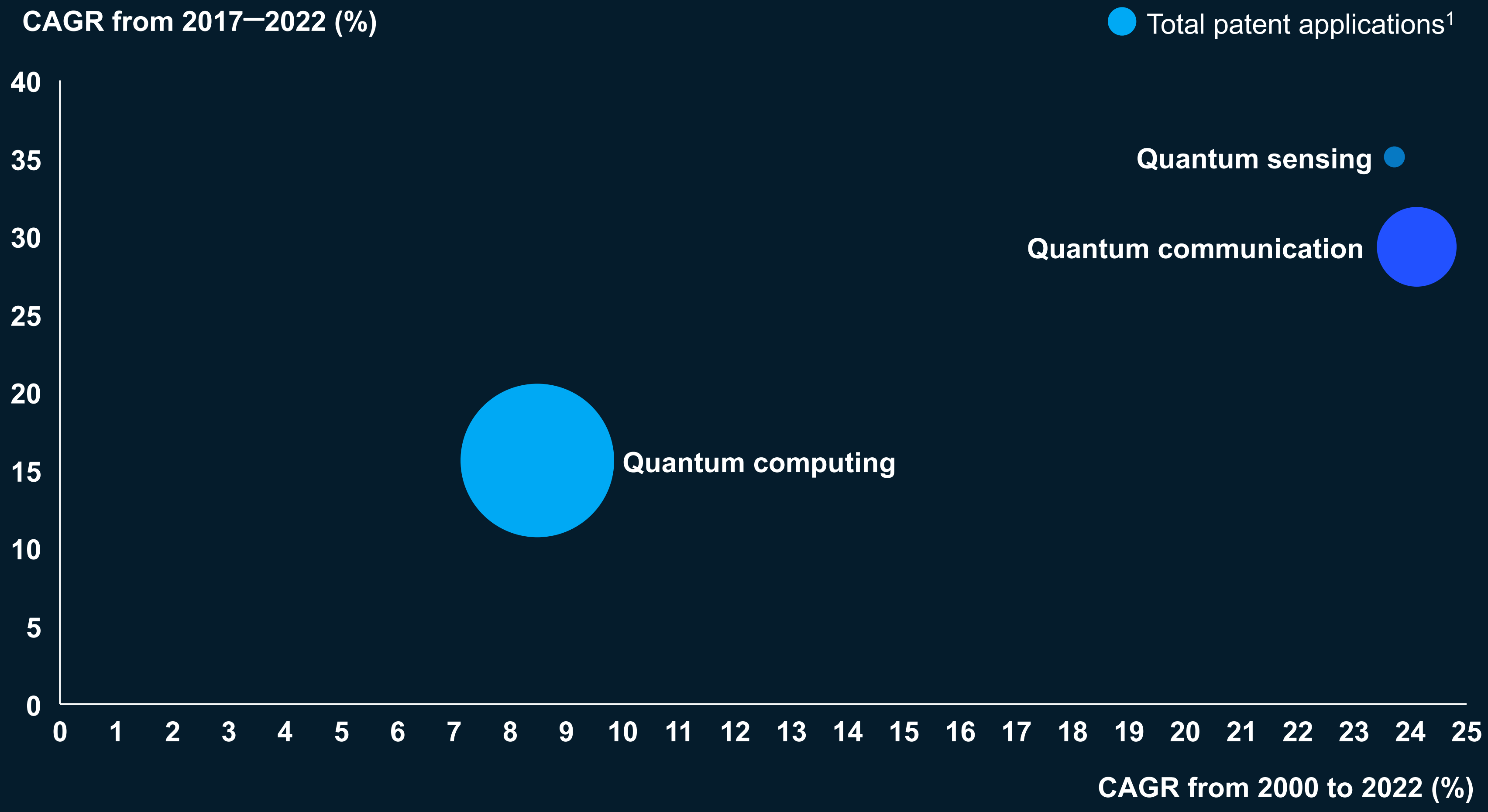
- QT patent applications decreased significantly for IBM and Google, with many other top players decreasing more gradually
- The number of patent applications peaked before 2021 for most top ten companies, except Baidu

[1]Companies ranked by cumulative number of patent applications.

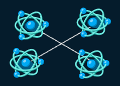
Source: IP analytics; Patsnap retrieved Jan 2024

Patent applications for QT accelerated over the past five years compared to the past two decades for QS and QC.

Growth rate for QT patent applications, 2000–2022



Patent applications for QS accelerated from 24% CAGR from 2000–22 to 35% CAGR from 2017–22



QComm had consistent growth in patent applications from 2000–22 (24% CAGR) and 2017–2022 (29% CAGR)

QC had slower growth of patent applications (8% CAGR) from 2000–22, which doubled to 16% CAGR from 2017–2022

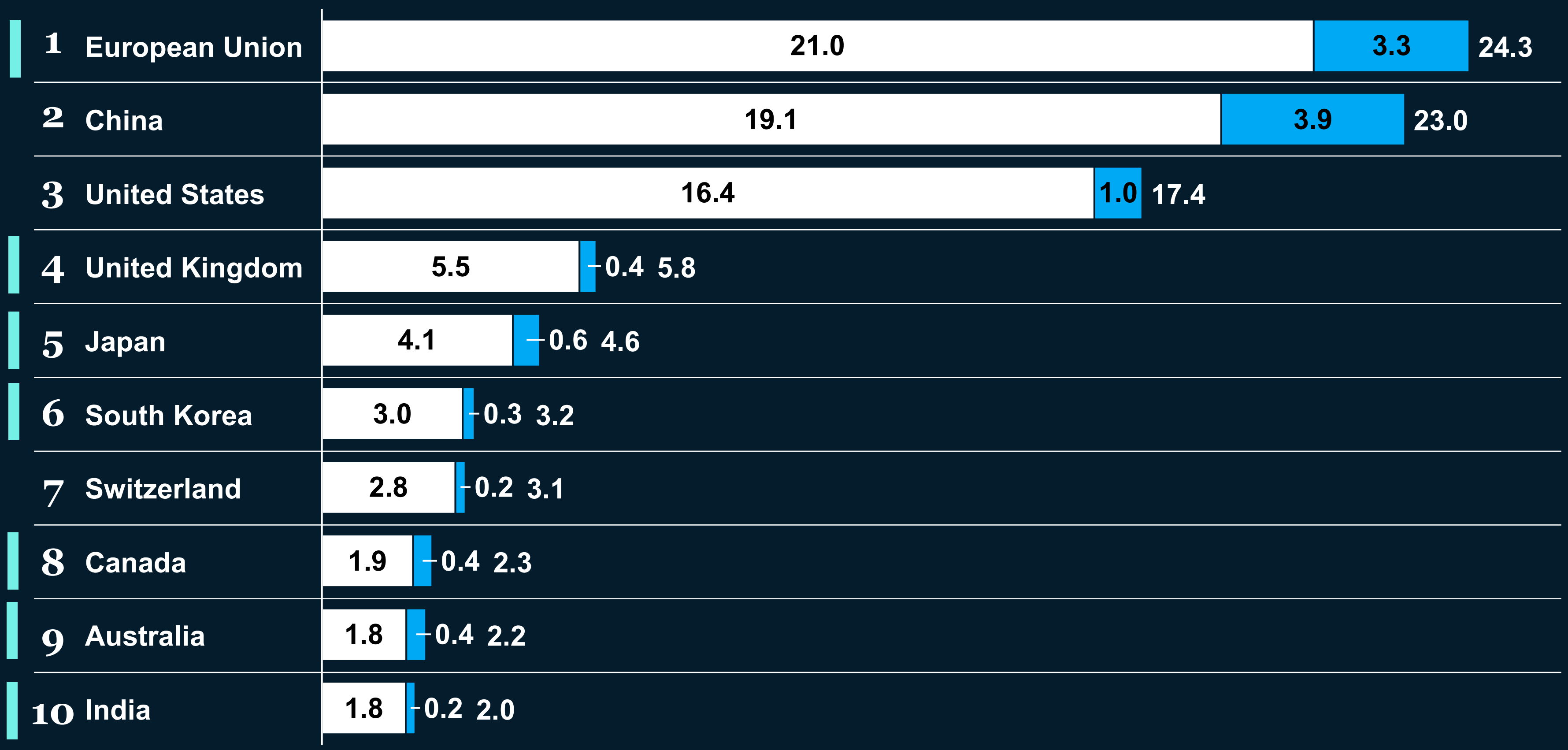
[1]Size of bubble represents total number of patent application from 2000 to 2022.

Source: IP analytics; Patsnap retrieved Jan 2024; McKinsey analysis

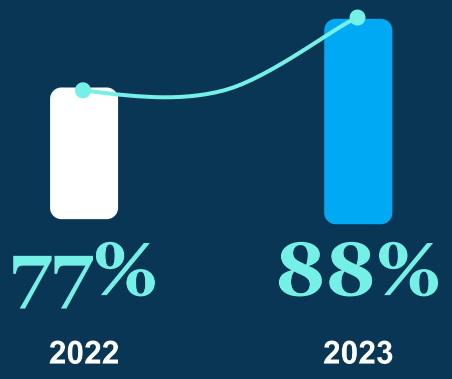
Scientists from EU institutions contribute most often to quantum-relevant publications.

2022[1] 2023[2] Public funding announced in 2023

Top 10 countries worldwide 2023, by share in scientific publications[1,2]
Share of authors from country's research institutions contributing to quantum-relevant publications,[3] %



Share by top 10



Insights

- Consolidation of the research publications among top ten countries increases from 77% to 88%
- The European Union leads in the largest number of scientific publications, followed by China and the United States
- Trend and ranking remains unchanged from previous year

[1]Includes publications from January 1, 2022, to December 31, 2022.
[2]Includes publications from September 1, 2022, to August 31, 2023.
[3]Quantum-relevant publications defined as publications in physical sciences.

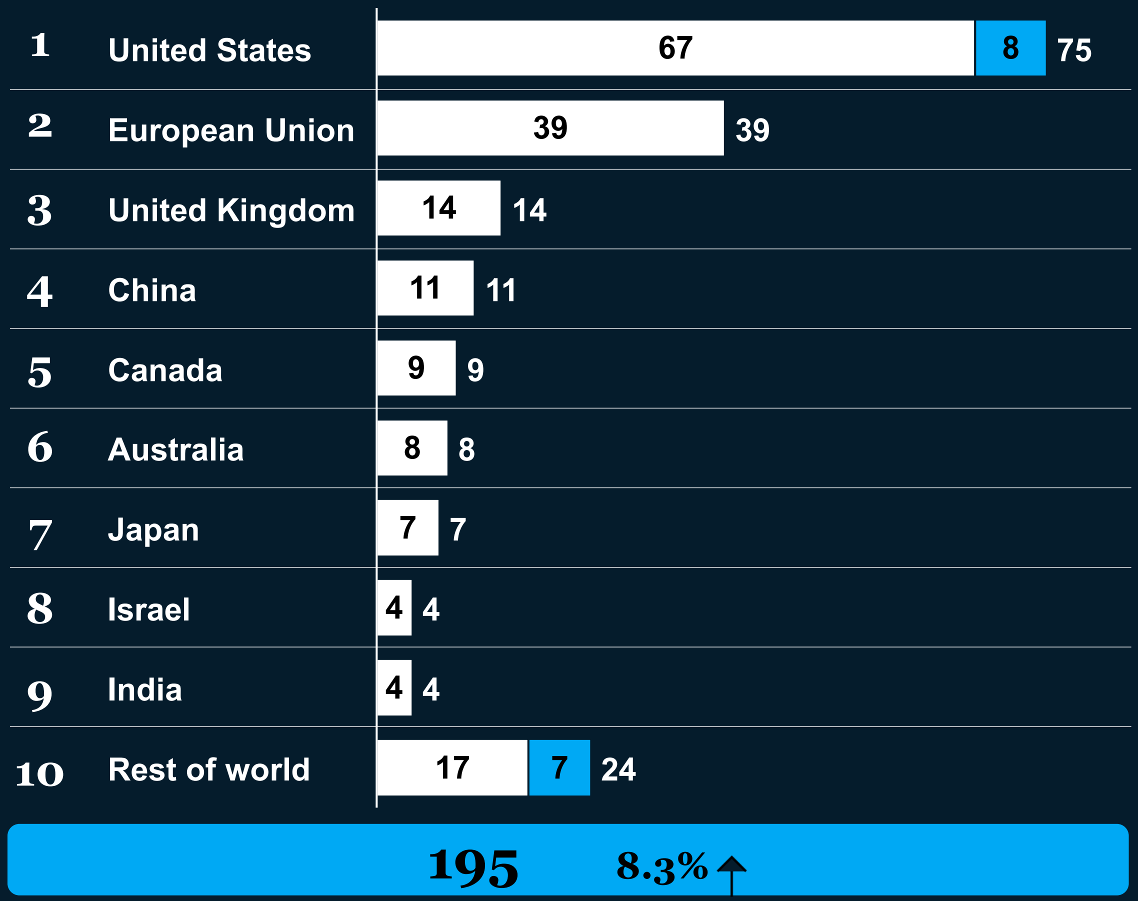
Source: Nature Index

Universities offering QT research programs and master's degrees increased significantly, with US and EU institutions in the lead.

2022 2023

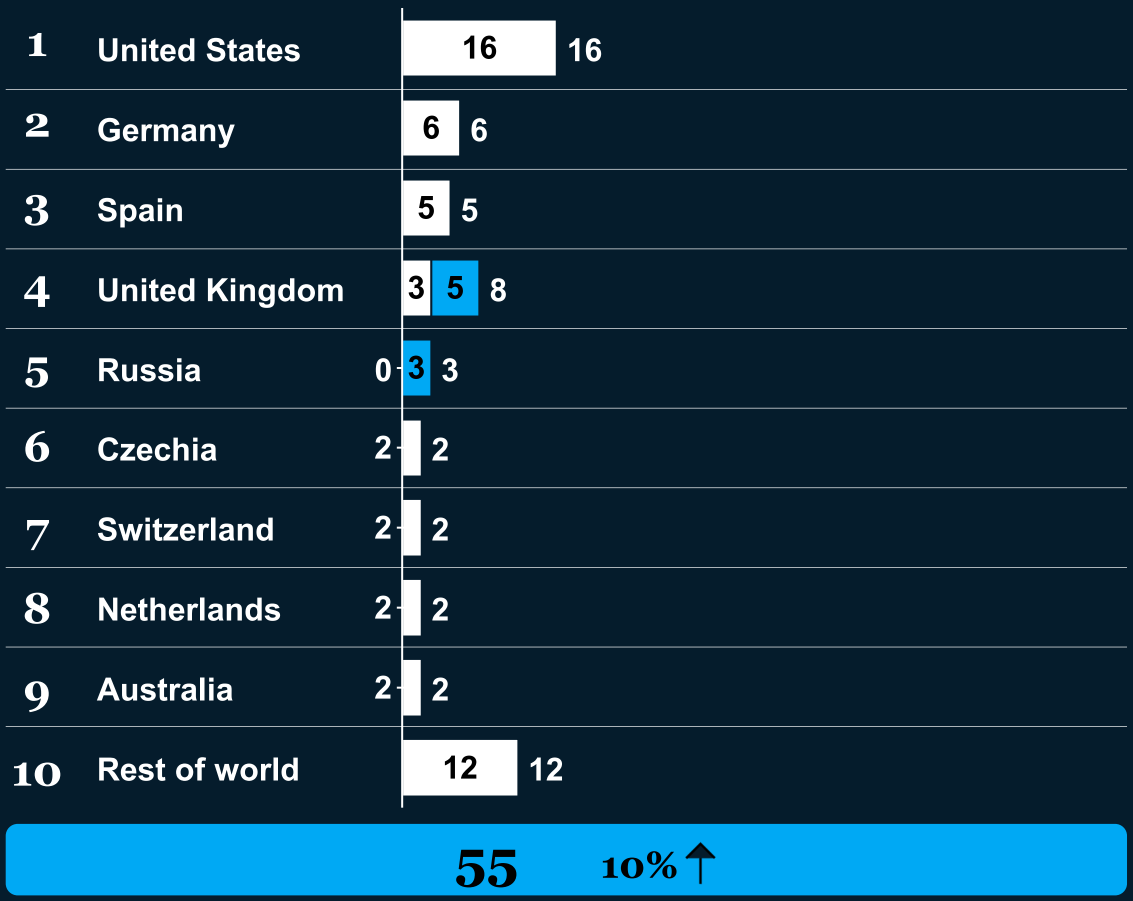
Top countries for universities with QT research programs, 2023

Number of universities per country



Universities offering QT master's degrees, 2023

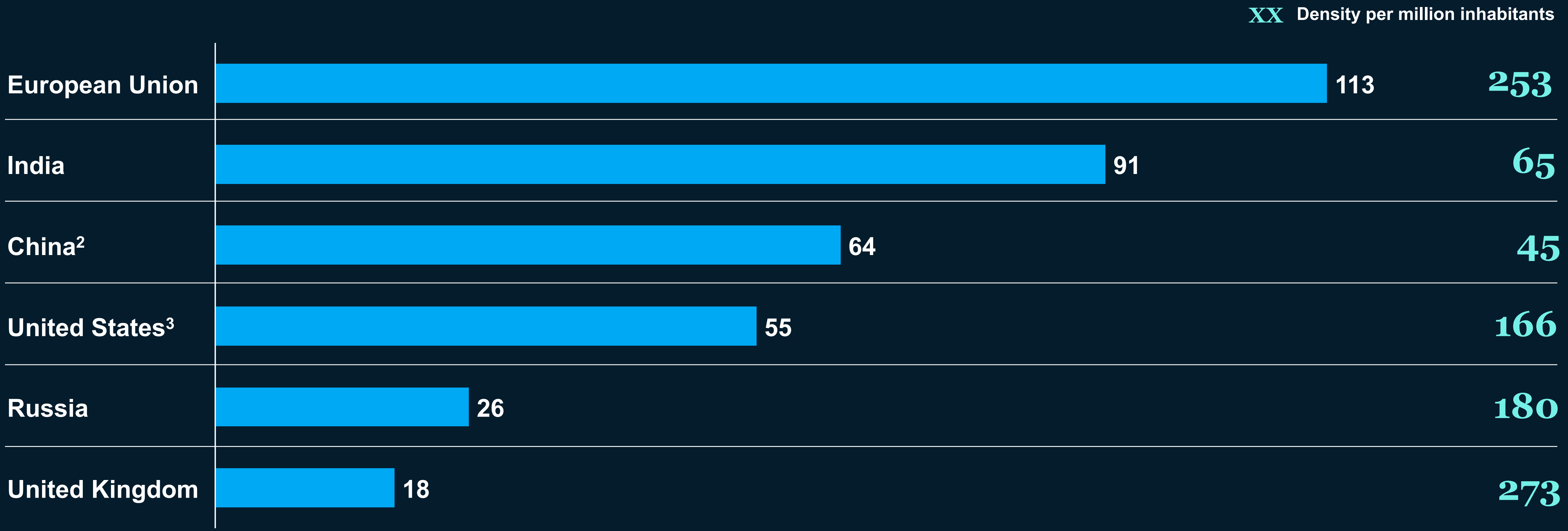
Number of universities per country



Source: QURECA; McKinsey analysis

The European Union has the highest number and concentration of QT talent.

Absolute number of graduates in QT-relevant fields (thousands),[1] 2021



~ 367k **Number of graduates in QT-relevant fields[3]**

[1]Graduates of master's level or equivalent in 2021 in biochemistry, chemistry, electronics and chemical engineering, information and communications technology, mathematics and statistics, and physics.
[2]High-level estimates.
[3]The actual talent pool for the United States may be larger, as bachelor programs are longer and master's programs are less common.

Source: National government websites; OECD

Quantum in North America

The United States leads the QT field in private funding and number of start-ups.

Not exhaustive

United States

Figures

~$3.75 billion
total public investment

~$3.8 billion
private investment

27%
of QT-related patents have been granted to researchers based in the United States

14
major research centers and institutes part of the National Quantum Initiative

Policies and news

December 2023, QuEra Computing announced the demonstration of quantum error correction executing large-scale algorithms with 48 logical qubits

December 2023, IBM announced Condor, a superconducting-qubit based chip with 1,121 qubits

November 2023, The National Quantum Initiative Reauthorization Act is passed by the US Congress, supporting the continued leadership of the United States in quantum information science and its technology applications

October 2023, Atom Computing announced the creation of an atomic array with 1,180 qubits

February 2023, Google announced the demonstration of quantum error correction with surface codes used to create logical qubits

Companies

Technology	Number[1]
Quantum computing	106
Quantum communication	20
Quantum sensing	16

Ecosystems or hubs

Boston Area Quantum Network
Chicago Quantum Exchange
Mid-Atlantic Quantum Alliance

[1]Pure-play companies focusing on one quantum technology.

Source: Press search; PitchBook; Patsnap

Canada

Significant public and private funding continued to support QT development in Canada, often as part of hubs.

Non-exhaustive

Figures

~$1.4 billion
total public investment

~$1.3 billion
private investment

11%
of QT-related patents have been granted to researchers based in Canada

Policies and news

November 2023, Photonic Inc., which is developing quantum computers using photonically linked silicon qubits, raised $100M

September 2023, IBM Canada and the Quebec Digital and Quantum Innovation Platform (PINQ2) unveiled Canada's first Quantum System One with a 127-qubit processor in Bromont, Quebec

March 2023, Ericsson Canada announces the creation of a quantum research hub in Montreal in partnership with the University of Ottawa and the University of Sherbrooke

March 2023, OVHCloud announces the purchase of the MosaiQ computer powered by a designed by Quandela

January 2023, launch of the National Quantum Strategy in Canada with an investment of $360M in quantum research, talent, and commercialization

Companies

Technology	Number[1]
Quantum computing	28
Quantum communication	10

Ecosystems or hubs

DistriQ Quantum Innovation Zone
Montreal Quantum Research Hub
Quebec Digital and Quantum Innovation Platform (PINQ[2])

[1]Pure-play companies focusing on one quantum technology.
Source: Press search; PitchBook; Patsnap

Quantum in Asia

Multiple Asian countries are catching up on quantum technologies, with bold funding commitments and technological advancements.

Greater China

Large companies, start-ups, and universities continue to pursue quantum technology development in China, supported by central and local governments; Taiwan aims to leverage its semiconductor development capabilities to develop quantum technologies

India

The Indian government made significant announcements including additional funding within the National Quantum Mission, and for research parks and tech hubs across the country to support an emerging start-up ecosystem

Japan

Japan had substantial development in quantum computing, including the announcement of Moonshot Goal 6, which aims to develop a fault-tolerant universal quantum computer by 2050

South Korea

The South Korean government has announced significant funding for quantum technology development to support goals for technology, commercialization, and talent

Israel

Israel has committed public funding to support quantum technology development, especially for quantum computing, and often though consortia to promote collaboration

In Greater China, government and private investment drives QT research and education.

Greater China

Not exhaustive

Figures

~$15.3 billion
total public investment[1]

~$359 million
private investment

11%
QT-related patents have been granted to researchers based in China

29
dedicated QT research institutions and labs

Policies and news

- The Chinese government's ongoing policies to accelerate the January 2024 Origin Quantum launches Origin Wukong, a superconducting qubit-based quantum computer with 72 computational qubits and 126 coupler qubits
- December 2023, scientists in China and Russia demonstrated quantum communication over 2,300 miles via an optical link with the satellite Mozi
- October 2023, Hon Hai Quantum Computing Research Institute launches laboratory for trapped ion–based QC
- September 2023, China Telecom Quantum Information Technology Group announced an investment of over $1.3B via a cooperation agreement with the Hefei National High-Tech Industry Development Zone
- May 2023, Bose Quantum released its self-developed 100-qubit coherent optical quantum computer

Companies

Technology	Number
Quantum computing	17
Quantum communication	23
Quantum sensing	8

Ecosystems or hubs

Hefei National High-Tech Industry Development Zone
National Taiwan University-IBM Quantum Computer Center

[1]Other sources put this figure at closer to ~$25 billion; this estimate is based on publicly available data (eg, China's five-year plans detailing the country's economic development goals).

Source: Patsnap; McKinsey analysis

India is taking significant steps toward establishing itself as an emerging global leader in quantum technology.

Not exhaustive

Figures

~$1.75 billion
public investment

~$2.4 million
private investment

~60
research labs for quantum technology

0.2%
of QT-related patents have been granted to researchers based in India

Policies and news

- India launched the National Quantum Mission in 2023 aiming to support scientific and industrial R&D, and to develop intermediate-scale quantum computers with 5–1000 physical qubits in 8 years
- October 2023, Samsung Semiconductor India Research and IISc-Bengaluru collaborated to promote quantum tech research
- September 2023, IIT Bombay partnered with Chicago Quantum Exchange (CQE) to facilitate research collaboration and develop a trained talent pool
- June 2023, BosonQ Psi partners with Tech Mahindra Makers Lab to expedite the adoption of quantum technology for a range of industrial applications
- March 2023, the first operational QC-based telecommunications network in India developed by the Centre for Development of Telematics was announced

Companies

Technology	Number
Quantum computing	6
Quantum communication	2

Ecosystems or hubs

The Indian government plans to create 21 quantum hubs and 4 quantum research parks across the country as a part of the National Quantum Mission

Source: Indian government; PitchBook; Patsnap; McKinsey analysis

Japan has announced ambitious QT goals and reached milestones including deploying three QC systems.

Not exhaustive

Figures

~$1.8 billion
total public investment

~$32 million
private investment

14%
of QT-related patents have been granted to researchers based in Japan

12
government-sponsored research labs

Policies and news

- Japan aims to create quantum unicorn venture companies by 2030 through the Quantum Future Society Vision
- The Japanese government's Moonshot Goal 6 aims to achieve fault-tolerant universal quantum computers by 2050
- December 2023, Japan launched its third quantum computer, which is accessible through a cloud platform and deployed at Osaka University's Toyonaka Campus
- October 2023, Fujitsu announced the successful development of a 64-qubit superconducting quantum computer in collaboration with RIKEN; Fujitsu launched a hybrid quantum computing platform that combines optimal quantum computing by linking a 64-qubit superconducting quantum computer and a 40-qubit quantum simulator.
- Aug 2023, SKY Perfect JSAT Corp. launched the Quantum Cryptography Optical Communication Device, for the Ministry of Internal Affairs and Communications
- March 2023, Japan's first domestically produced quantum computer, Ei, became operational at RIKEN

Companies

Technology	Number
Quantum computing	19
Quantum communication	4

Ecosystems or hubs

- National Institute of Advanced Industrial Science and Technology in Quantum-AI Technology
- RIKEN Center for Quantum Computing (RQC)
- Tokai National Higher Education and Research System in Quantum Frontier Industry Development Hub
- Quantum Strategic Industry Alliance for Revolution (Q-STAR)

Source: Patsnap; McKinsey analysis

South Korea announced ambitious goals and significant funding to support quantum technology development.

South Korea

Not exhaustive

Figures

~$2.33 billion
public investment by 2035

~$62 million
private investment

3%
of QT-related patents have been granted to researchers based in South Korea

Policies and news

- February 2024, IBM announced Korea Quantum Computing engaged IBM to offer AI software and infrastructure, including plans to deploy an IBM Quantum System Two quantum computer in Busan by 2028
- February 2024, PASQAL announced a partnership with Korea Advanced Institute of Science and Technology and the City of Daejeon
- September 2023, QuEra Computing, the Sejong Special Autonomous City, and Korea Advanced Institute of Science and Technology announced a partnership to establish a quantum industry ecosystem in Sejong City
- June 2023, South Korea announced a national quantum science strategy with a planned investment of over $2.3B through 2035. National strategy goals include increasing the number of quantum technology companies and talent, and gaining 10% of the global market share in quantum technology by 2035
- April 2023, the governments of the United States and South Korea issued joint statement on cooperation in quantum information science and technologies

Companies

Technology	Number
Quantum computing	1
Quantum communication	3

Ecosystems or hubs

Korea Quantum Industry Association (KQIA)
Daedeok Quantum Cluster

Source: Patsnap; McKinsey analysis

Israel is committing public funding to help support QT development consortia and ecosystems.

Not exhaustive

Figures

~$ 368 million
total public investment

~$152 million
private investment

1%
of QT-related patents have been granted to researchers based in Israel

Policies and news

April 2023, Quantum Source, which focuses on developing a photonic quantum computer, raised $12M to extend its seed round to $27M

March 2023, Quantum Machines, which offers quantum control solutions, and NVIDIA announced DGX Quantum, a GPU-accelerated quantum computing system

January 2023, the Israel Innovation Authority announced funding of ~$32M over three years for a new quantum computing consortium that will explore superconducting, trapped-ion, and photonic qubit technologies in a full-stack quantum computing solution

Companies

Technology	Number[1]
Quantum computing	8

Ecosystems or hubs

Israeli quantum computing center

[1]Pure-play companies focusing on one quantum technology.

Source: PitchBook; Patsnap; McKinsey analysis

Quantum in Europe

European nations are building ecosystems for QT development and setting ambitious goals to lead in quantum technology.

France

France has supported $1.3 billion of funding over 5 years, including public and private investments for quantum technologies research and workforce development

Germany

Germany announced an additional $2.25 billion for quantum technologies over 3 years to create a 100-qubit universal quantum computer and develop quantum technologies aiming to secure technological sovereignty and leadership

Italy

Italy leverages national funding and regional strategies to support the development of quantum technologies and ecosystems

United Kingdom

The United Kingdom has committed $3.1 billion over one decade to create a leading quantum-enabled economy and garner support from private investments

Netherlands

The Netherlands has a robust ecosystem for quantum technology that supports several emerging start-ups

Finland

Finland has a number of start-ups focused on software and hardware for quantum computing

France combines national and EU funding with private investments for QT development.

Not exhaustive

Figures

~$2.2 billion
total public investment

~$113 million
private investment

11%
of QT-related patents have been granted to researchers based in France

21
research labs part of the Paris Centre for Quantum Technologies

Policies & News

French President announced the National Quantum Computing Plan in 2021, which supports $1.3B of funding for quantum technologies over 5 years

The French government hopes to create 16,000 new jobs within the quantum technology sector by 2030

December 2023, Alice & Bob announced the tape out of Helium 1, a 16-qubit quantum processing unit that combines cat qubits for error correction

November 2023, Quandela, a start-up building photonics-based quantum computers, raised $54M in Series B funding

July 2023, Quobly, a start-up building silicon qubit-based quantum computers, raised $20M in seed round funding

January 2023, PASQAL, a start-up building neutral atom-based quantum computers, raised $107M in Series B funding

Companies

Technology	Number
Quantum computing	11
Quantum communication[1]	4
Quantum sensing	7

Ecosystems or hubs

Paris Centre for Quantum Technologies
High-Performance Computer and Quantum Simulator hybrid
EuroQCS-France photonic quantum computer

[1]Includes companies that offer post-quantum cryptography solutions.

Source: PitchBook; Patsnap; Olivier Ezratty, *Understanding Quantum Technologies*, 2023; McKinsey analysis

Germany has ambitious plans for quantum technologies, as reflected by industry and academic developments.

Germany

Not exhaustive

Figures

~$5.2 billion
total public investment

~$104 million
private investment

12%
of QT-related patents have been granted to researchers based in Germany

13
companies are part of the Quantum Technology and Application Consortium

Policies and news

In April 2023, the German government announced the Action Plan for Quantum Technologies, which provides $2.25B in funding over 3 years to build a universal quantum computer by 2026

The Action Plan also aims to drive practical applications of quantum technology and foster ecosystems for bringing quantum technologies to market

In June 2023, IBM announced plans to build its first Europe-based quantum data center in Ehningen, with multiple QC systems each with >100 qubits expected to be operational in 2024

Companies

Technology	Number[1]
Quantum computing	11
Quantum communication	4
Quantum sensing	5

Ecosystems or hubs

Munich Quantum Valley, Munich Center for Quantum Science and Technology, Center for Integrated Quantum Science and Technology (in Stuttgart, Ulm)
DLR Quantum Computing Initiative (innovation centers based in Ulm and Hamburg)
Quantum Technology and Application Consortium (QUTAC)

[1]Includes technologies along the value chain that span multiple quantum technology domains, including, for example, hardware components.

Source: PitchBook; Patsnap; McKinsey analysis

Italy is using EU funding and regional strategies to fund quantum technology development.

Not exhaustive

Figures

~$144 million
total public investment

—
No reported private investment

2%
of QT-related patents have been granted to researchers based in Italy

~70
academic and industry partners as part of Italian QT system

Policies and news

NQSTI[1] consortium, launched in January 2023, is funded under NextGenerationEU and supports quantum technology education, technology transfer, and societal outreach

ICSC[2]'s Spoke 10 focuses on QC applications, hardware/software, and scalability

QUID project within the EuroQCI Infrastructure develops 13 QMANs in Italy connected to the IQB, and regions have developed strategies following the European Union to create ecosystems for start-ups and spinoffs

February 2024, Italy's first permanent multi-nodes multi-vendor quantum metropolitan area network, connected to the Italian Quantum Backbone, is inaugurated in Naples and funded by the Competence Center Meditech by Italian Ministry of Enterprises and Made in Italy

April 2023, SEEQC demonstrated "Italy's first full-stack quantum computer" SEEQC System Red, developed in a joint lab with Federico II University in Naples

Companies

Technology	Number
Quantum computing	2
Quantum communication	3
Other[3]	2

Ecosystems or hubs

National Quantum Science and Technology Institute
High-Performance Computing, Big Data & Quantum Computing Research Centre
Italian Quantum Backbone

[1]National Quantum Science and Technology Institute
[2]ICSC National Research Centre for High-Performance Computing, Big Data & Quantum Computing.
[3]Includes technologies that span multiple quantum technology domains (eg, photonics) and other quantum technologies (eg, materials science); excludes companies with significant Italian footprint but not headquartered in Italy (eg, SEEQC).

Source: Press search, UNINA, CDC Meditech, QTI, PitchBook, Patsnap

The UK government has committed significant funding to building a leading quantum-enabled economy by 2033.

United Kingdom

Not exhaustive

Figures

~$4.3 billion
total public investment

~$1.5 billion
private investment

3%
of QT-related patents have been granted to researchers based in the UK

24
universities are part of National Quantum Technologies Programme hubs

Policies & News

The UK government's National Quantum Strategy has committed an additional $3.1B over 10 years from 2024, which also aims to generate $1.3B in private investment, for the United Kingdom to be a leading quantum-enabled economy by 2033

By 2033, the United Kingdom aims to maintain top 3 position in the quality of quantum science publications and fund 1,000 additional post-graduate research students in quantum-relevant disciplines

In February 2024, the UK government announced a $57M investment for quantum technologies, including awards to seven companies to build test beds at the NQCC[1]

Companies that are building test beds at the NQCC include UK-based ORCA Computing, Oxford Ionics, Aegiq, and Quantum Motion

Companies

Technology	Number
Quantum computing	25
Quantum communication[2]	14

Ecosystems or hubs

National Quantum Technologies Programme[3]
National Quantum Computing Centre, Quantum Metrology Institute
UKQuantum

[1]National Quantum Computer Centre.
[2]Includes quantum-secure cryptography.
[3]Includes four hubs: Quantum Computing and Simulation Hub, Quantum Communications Hub, UK Quantum Technology Sensors and Timing Hub, and UK Quantum Technology Hub in Quantum Enhanced Imaging.

Source: PitchBook; Patsnap; McKinsey analysis

Netherlands

An emerging QT start-up ecosystem is developing in the Netherlands, stemming from research hubs.

Not exhaustive

Figures

~$1 billion
total public investment

~$40.5 million
private investment

2%
of QT-related patents have been granted to researchers based in the Netherlands

5
hubs as part of Quantum Delta NL

Policies and news

January 2024, QphoX raised $8.7M to develop interconnects between quantum computers toward a quantum internet

March 2023, investor Quantum Delta NL Participations announces a $16.3M fund dedicated to helping Dutch start-ups in QT

September 2023, Delft Circuits raised $6.8M to develop interconnects that interface with cryogenic quantum hardware

July 2023, Quantum Delta NL announced $66M funding from The National Growth Fund, a contribution to the trilateral agreement with France and Germany

Companies

Technology	Number
Quantum computing	8
Quantum communication[1]	3
Quantum sensing	1

Ecosystems or hubs

Quantum Delta NL hubs (Delft, Eindhoven, Leiden, Twente, Amsterdam)
Quantum Internet Alliance (coordinated by QuTech)

[1]Pure-play companies focusing on one quantum technology.

Source: Press search; PitchBook; Patsnap

Finland

Finland has both hardware and software start-ups focusing on quantum computing.

Not exhaustive

Figures

~$27 million
total public investment

~$248 million
private investment

1%
of QT-related patents have been granted to researchers based in Finland

11
research groups part of Quantum Technology Finland

Policies and news

September 2023, IQM Quantum Computers and VTT Technical Research Center of Finland announces the completion of Finland's second quantum computer with 20 qubits

June 2023, Algorithmiq, which specializes in quantum computing applications for life sciences, raised $15M in a series A funding

Companies

Technology	Number
Quantum computing	7

Ecosystems or hubs

Quantum Technology Finland

Source: Press search; PitchBook; Patsnap

Quantum technology innovation clusters

Collaboration among industry, academia, and government is critical toward overcoming challenges for QT development.

Technological challenges

- Access to **state-of-the-art hardware and infrastructure** (eg, specialized software, electronics, manufacturing and nanofabrication capabilities)
- **Uncertainties** in timing and nature of the fundamental research **breakthroughs** required for real world deployment (eg, quantum error correction)
- Addressing **useful applications** with nascent quantum technologies (eg, large-scale QC required for many applications)

Ecosystem challenges

- **Limited awareness and adoption** of quantum technologies (eg. differing levels of technology maturity and applicability for different industries)
- Lack of **interdisciplinary coordination** required to bring technologies to market (eg, between academia and industry)
- Quantum companies struggling to address the **talent gap,** which hinders development and innovation (eg, talent includes theory, hardware, software development)

Collaboration among industry, academia, and government is essential to accelerating development of quantum technology, including industrializing technology, managing intellectual property, and overcoming talent gaps

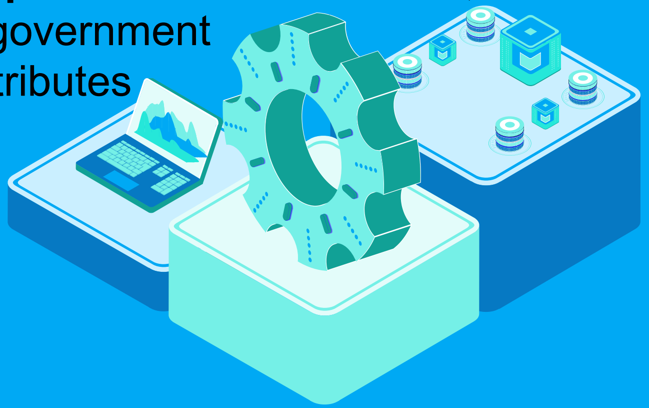
Source: McKinsey analysis

Emerging clusters will accelerate the development of quantum technologies.

Ecosystems are emerging worldwide that involve **multiple stakeholders** working jointly toward a **common goal of advancing quantum technologies**

Developing and scaling such **regional innovation ecosystems** (including research consortia) will be a determining factor for achieving wide adoption and commercialization of quantum technology

A **quantum technology cluster** is described as a **network of relationships** between researchers, industry partners, and government entities, and which contributes to the **technological advancement** of quantum technologies and drives **regional value creation**



What a tight collaboration provides

1. **Fostering extensive collaboration** between theoreticians, technologists, and stakeholders
2. **Coordination for developing inter-disciplinary solutions** to complex challenges
3. **Access to research and manufacturing capabilities** and **enabling integration** into existing infrastructure
4. **Enabling rapid commercialization and scaling** to shorten time-to-value for innovation
5. Helping **inform and prioritize key areas for investment**
6. **Better preparing talent** who gain relevant skills and experience

Source: McKinsey analysis

Building innovation ecosystems and clusters requires a range of support actions from stakeholders.

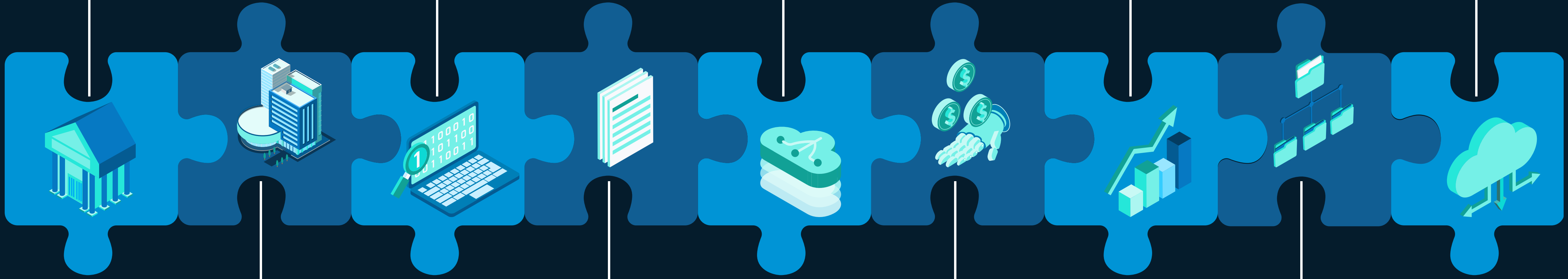
Government
- Develop national quantum strategy
- Identify priority innovation areas for investment
- Address policy challenges
- Foster effective local ecosystems

Research institutions
- Develop beyond-the-state-of-the-art quantum technologies
- Partner with relevant players to collaborate on full-stack quantum solutions

Corporate end users
- Develop quantum adoption road maps
- Co-develop technology
- Build quantum workforce
- Utilize quantum as a service

Start-up accelerator programs
- Operate as exclusively quantum-focused programs to grow quantum start-ups
- Offer coaching and necessary platform for start-ups to take ideas into implementation

Infrastructure
- State-of-the-art equipment
- Capital investments
- Talent
- Physical space
- Training and education



Quantum companies
- Experiment with proofs of concept
- Build strategic road map up to integration into business
- Build internal quantum workforce
- **Start-ups:**
  - — Obtain funding
  - — Receive mentorship from network

Academia (Education & Research)
- Train and educate the next generation of talent in quantum and related areas
- Produce cutting-edge research
- Design study programs for quantum

Investors
- Access expertise in technology to inform investment avenues
- Prioritize high-potential technologies
- Access cluster's start-up network for investment

Administrative organization
- Interface with cluster members for strategic partnerships in research, knowledge and technology transfer, and workforce and ecosystem development
- Manage a portfolio of industry partners to spur the creation and growth of ventures

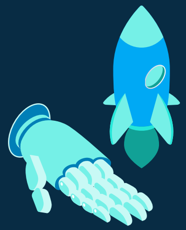
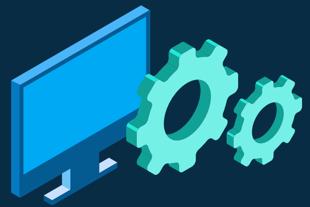
Source: McKinsey analysis

What are the key enablers that must be in place to accelerate research in QT?

Source: McKinsey analysis

Successful innovation clusters require ecosystems comprising academic research, start-ups, accelerators, and industry partners.

Not exhaustive

	 Academic research	 Start-ups	 Accelerators	 Industry partners
Description	• Provides cutting-edge innovations, training, and education for quantum technology talent, and physical infrastructure • Often provides incubator anchor for innovation cluster	• Provide state-of-the art technologies being developed and deployed for commercialization • Key requirements include capital investments, physical infrastructure, mentorship, and talent	• Provide mentorship and training for commercializing quantum technologies, and early-stage funding • Often associated with academic institutions and naturally part of ecosystem	• Provides real-world requirements for quantum technology, infrastructure, and funding • Often are the initial large source of market demand for a quantum technology, including as part of own research and development
Examples Chicago	University of Chicago Northwestern University Argonne National Laboratory Fermilab	EeroQ memQ qBraid	Duality	Boeing IBM
Delft	TU Delft TNOQuTech	Q-Bird QuantWare Single Quantum Orange Quantum Systems Qblox QphoX	Infinity	Intel Fujitsu Juniper Networks

Source: McKinsey analysis

Quantum computing

The United States and Canada still have the most vibrant QC start-up communities.

Number of QC start-ups by country, 2023

Not exhaustive

+ change since 2022

		Start-ups		Incumbent companies	Public/ government organizations	Academic groups	
Top 7	United States	75	+3	9	18	70	+3
	Canada	28		0	2	10	+1
	United Kingdom	24	+2	1	2	14	
	Japan[1]	14		1	0	7	
	France	11		1	3	9	
	Germany	11		2	1	7	
	China[1]	10	+1	2	12	11	
Rest of world		88	+4	1	19	55	+1
Total		**261**	+10	**17**	**57**	**185**	+5

[1]There is limited transparency into commercial activity in China, and to a lesser extent for Japan. We think Chinese activity in quantum technologies is primarily through government-funded research institutions.

Source: CapitalIQ; Crunchbase; PitchBook; Quantum Computing Report; McKinsey analysis

QC start-ups continue to emerge across the globe, with the United States, United Kingdom, and European Union launching the most.

Number of QC start-ups by country[1]

Not exhaustive

+ indicates change since 2021

Country	2023	2022	2021
United States	76 +3	72	60
Canada	28	28	26
United Kingdom	24 +1	22	19
Japan[1]	14	14	13
Germany	12 +1	12	8
France	11	11	8
China[1]	10 +1	9	8
Australia	8	8	7
Spain	8	8	7
Netherlands	7	7	6
Finland	7 +1	6	6
India	6	6	5
Israel	6	6	4

Country	2023	2022	2021
Switzerland	5	5	5
Sweden	3	3	2
Denmark	3	3	2
Colombia	2	2	2
Poland	3 +1	2	2
Singapore	2	2	2
Austria	3 +1	2	2
UAE	2	2	2
Italy	2	2	1
Czech Republic	1	1	1
Estonia	1	1	1
Greece	1	1	1
Hong Kong	1	1	1

Country	2023	2022	2021
Bulgaria	1	1	1
Liechtenstein	1	1	1
Philippines	1	1	0
Norway	2 +1	1	1
Portugal	2	1	1
Romania	1	1	1
Russia	1	1	1
Taiwan	1	1	1
Turkey	1	1	1
Uruguay	1	1	1
Ireland	1	1	1
South Korea	1	1	0
Grand total	**261** +10	**251**	**212**

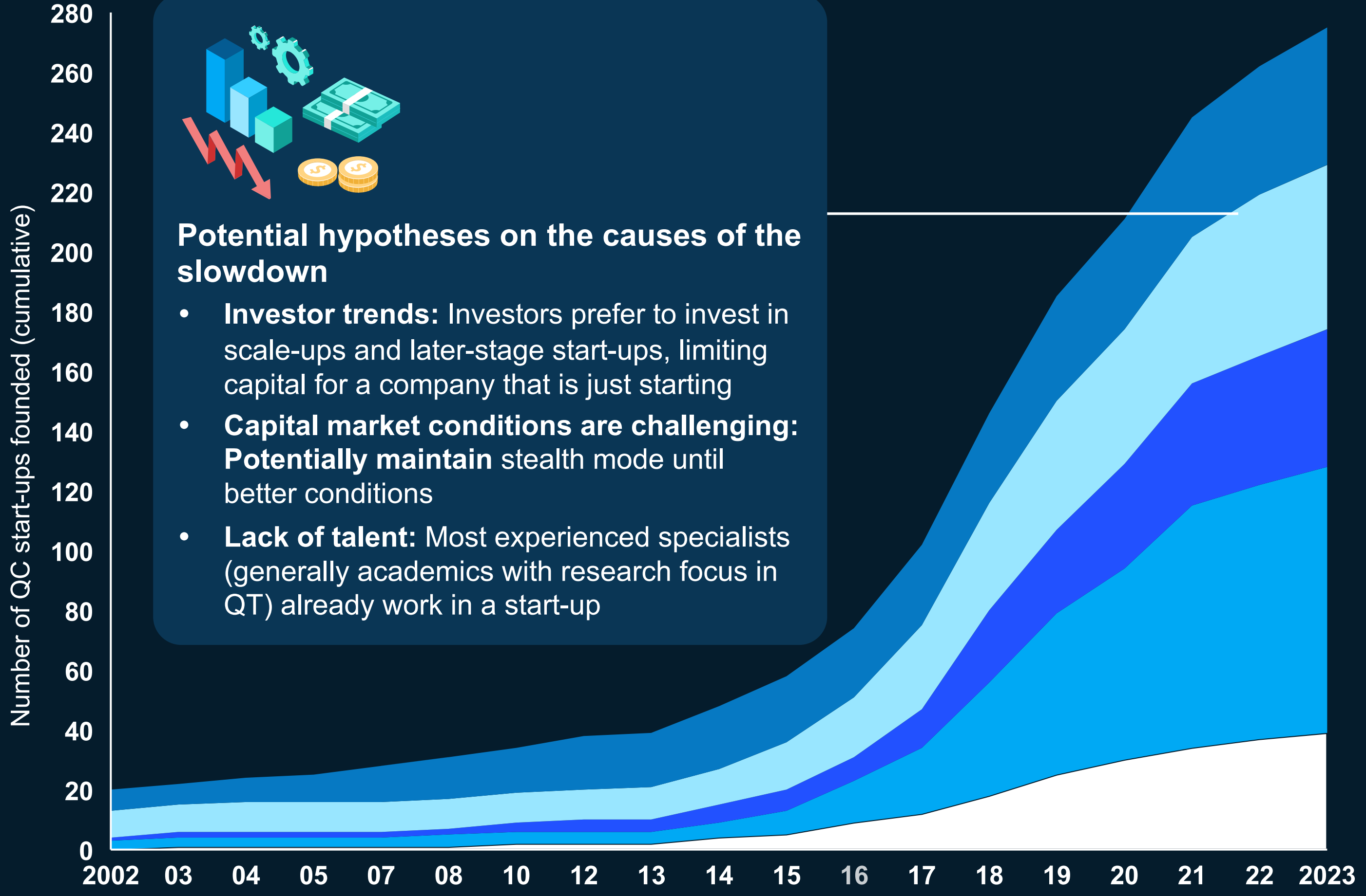
[1]There is limited transparency into commercial activity in China, and to a lesser extent for Japan. We think Chinese activity in quantum technologies is primarily through government-funded research institutions.

Source: CapitalIQ; Crunchbase; PitchBook; Quantum Computing Report; McKinsey analysis

The rate of publicly announced QC start-up creation has slowed over the past four years.

Not exhaustive

Components | Hardware | Systems software | Application software | Services



Potential hypotheses on the causes of the slowdown

- **Investor trends:** Investors prefer to invest in scale-ups and later-stage start-ups, limiting capital for a company that is just starting
- **Capital market conditions are challenging: Potentially maintain** stealth mode until better conditions
- **Lack of talent:** Most experienced specialists (generally academics with research focus in QT) already work in a start-up

Number of QC companies founded each year

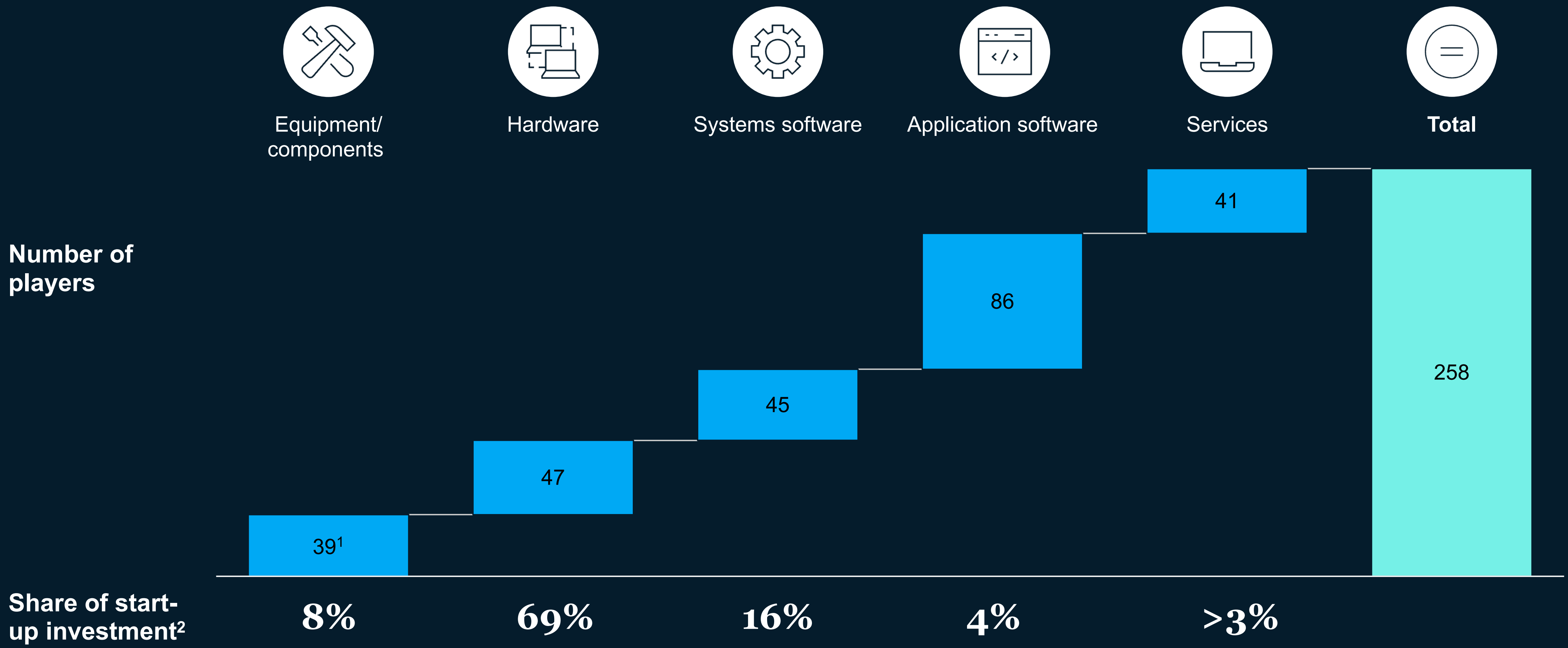
	2018	2019	2020	2021	2022	2023
Components	3	5	2	3	3	3
Hardware	8	7	2	4	5	1
Systems software	11	4	7	6	2	2
Application software	16	16	10	17	4	2
Services	6	7	5	4	3	2
Sum	44	39	26	34	17	10

–11% | –33% | +31% | –50% | –41%

Source: CapitalIQ; Crunchbase; PitchBook; Quantum Computing Report; McKinsey analysis

Among QC value-chain start-ups, hardware manufacturers continue to see the most investment.

Number of QC start-ups, by value-chain segment



[1]There are more than 100 total suppliers; however, only 36 are start-ups specific to quantum computing.
[2]Based on public investments in start-ups recorded on PitchBook and announced in the press; includes announced deals for 2022; excludes investments in internal QT departments or projects by incumbents; actual investment is likely higher.

Source: CapitalQ; Crunchbase; PitchBook; Quantum Computing Report; McKinsey analysis

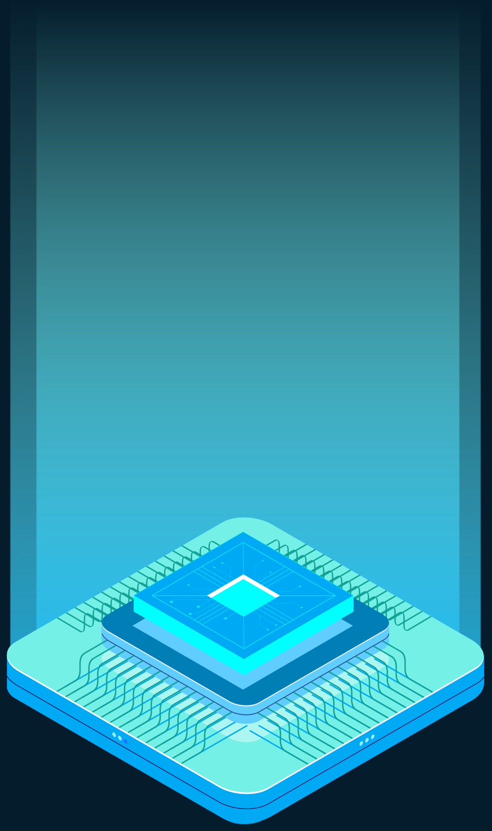
Technology deep dives

As we advance from the current NISQ era toward eventual large-scale, fault-tolerant quantum computing, quantum control and benchmarking become increasingly important.

Here are some perspectives

1. **Quantum control**
2. **Benchmarking**

Quantum control



What is quantum control?

Quantum control is a driving force of technological progress for quantum computing, **enabling improvements** from the **hardware** at the bottom of the quantum stack **to low-level systems software.**

What does quantum control enable?

Quantum control enables quantum computers to **scale from labs to commercial viability.**

Quantum control on low-level system software is enabling further **performance improvements** of algorithms and better quantum error correction (QEC).

What are the recent breakthroughs and outlook?

Challenges lie ahead in overcoming physical constraints and limitations of electronics of the underlying quantum system. Six key challenges to scaling and performance are identified, and current technological breakthroughs are listed in the coming pages.

Why should quantum business leaders care now?

Quantum systems can be **made useful in a shorter timeframe** by focusing and optimizing quantum control as a key enabler.

Control is crucial for scaling up quantum computers. To make quantum computing practical for solving real-world problems, control technology must overcome various scaling challenges.

Source: McKinsey analysis

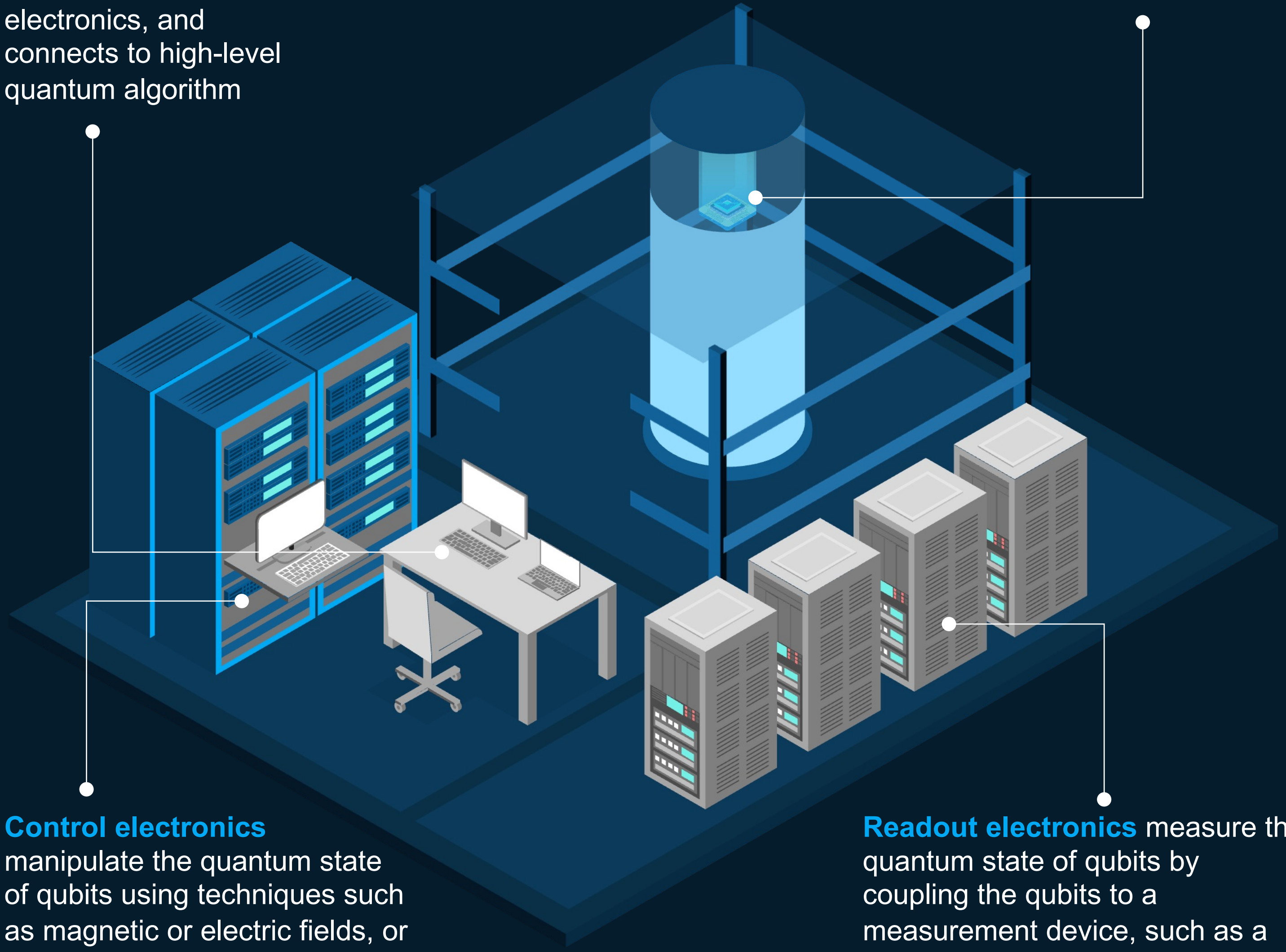
Superconducting circuits (illustrative)

Quantum control links the classical to the quantum world through dedicated software and hardware components.

Today, a quantum computer (eg, superconducting) has various hardware and software components, including quantum control components that require space and span meters

Control software operates and manages control and readout electronics, and connects to high-level quantum algorithm

Quantum chip contains qubit implementation and the electronic interface to drive the operations on the qubit; control is required for state preparation, state-to-state transfer, and gate transformation



Control electronics manipulate the quantum state of qubits using techniques such as magnetic or electric fields, or interacting with the qubits using other quantum systems

Readout electronics measure the quantum state of qubits by coupling the qubits to a measurement device, such as a resonator or a detector, and measuring the output of the device

Source: McKinsey analysis

Quantum control helps to detect, mitigate, and handle noise.

Sources of noise

1 **Device-based noise** caused by imperfections in the physical hardware or qubit technology used to construct the quantum computer (eg, bit flips, phase flips, and crosstalk)

2 **Control-related noise** caused by interactions between the quantum hardware and its surroundings (eg, thermal fluctuations, electromagnetic interference)

Innovative qubit topologies protect against device-based noise:

Cat qubits: Achieve protection against bit flips by applying two-photon injection system to maintain entropy, thereby preventing decoherence without extracting information[1]

Majorana fermions: Significant noise reductions over neutral atoms and trapped ions as they store information nonlocally making them intrinsically immune to noise[2]

Role of quantum control

Common ways to tackle quantum noise are improving the physical isolation of qubits, **developing precise control techniques**, and implementing quantum error-correction codes. This includes:

Error detection
Gate and readout infidelity needs to be detected efficiently. The noise itself can be seen as a signal as well to calibrate instruments.

Error handling
Errors can be handled during run-time by

- Quantum error correction
- Gate error mitigation
- Readout error mitigation

[1]Pursued by Alice & Bob; see https://arxiv.org/pdf/2307.06617.
[2]Pursued by Microsoft; see https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.220504.

Source: McKinsey analysis

Quantum control plays a significant role in large-scale and high-performance execution of quantum computing.

Role of quantum control

Quantum computing requires precise control of qubits and manipulation of the physical systems, achieved through quantum gates generated by microwaves, lasers, or optical fields and other techniques based on underlying qubit implementation. Beyond conventional electronics, a tailored quantum control system is needed to achieve optimal algorithmic performance.

What industry needs to solve

How can quantum control be optimized in terms of technology, configuration, and design such that we can:

- Improve the performance of existing quantum computers, and
- Achieve large-scale quantum computers in the near-term future?

Complexities of control and the number of areas that need to be solved for quantum computing to be economically viable are yet to be addressed.

What experts say

Quantum control involves **manipulating quantum systems through external fields or controls** to achieve desired results, thereby improving their functionality and behavior for various applications[1]

Quantum control is concerned with the fundamental **interaction between the classical and quantum worlds**[2]

Unlike in classical control, **quantum state information is harder to obtain** without disturbing the quantum system[3]

[1]ttps://thequantuminsider.com/2023/07/19/quantum-control/
[2]https://q-ctrl.com/topics/what-is-quantum-control
[3]https://www.quantamagazine.org/why-is-quantum-computing-so-hard-to-explain-20210608/

Source: McKinsey analysis

Six main challenges stand between quantum control and high-performance, large-scale quantum computing.

Small-scale quantum systems with limited quantum control

Improve control performance

1. **Noise challenge**
Control needs to shield qubits from non-device-based noise

2. **Measurement challenge**
Limited precision in control electronics forces large number of qubits needed

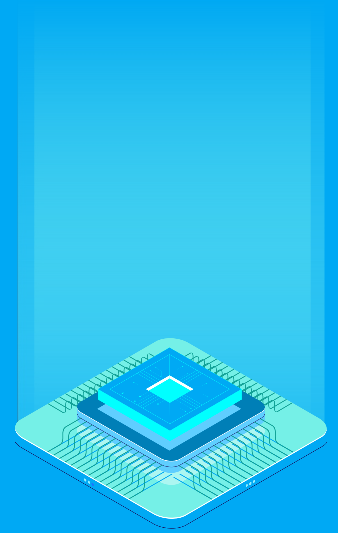
3. **Standardization challenge**
Tailored control and calibration is required for each individual qubit

Enable qubit scalability

4. **Resource challenge**
Resource capacity constraints make increased number of qubits unfeasible

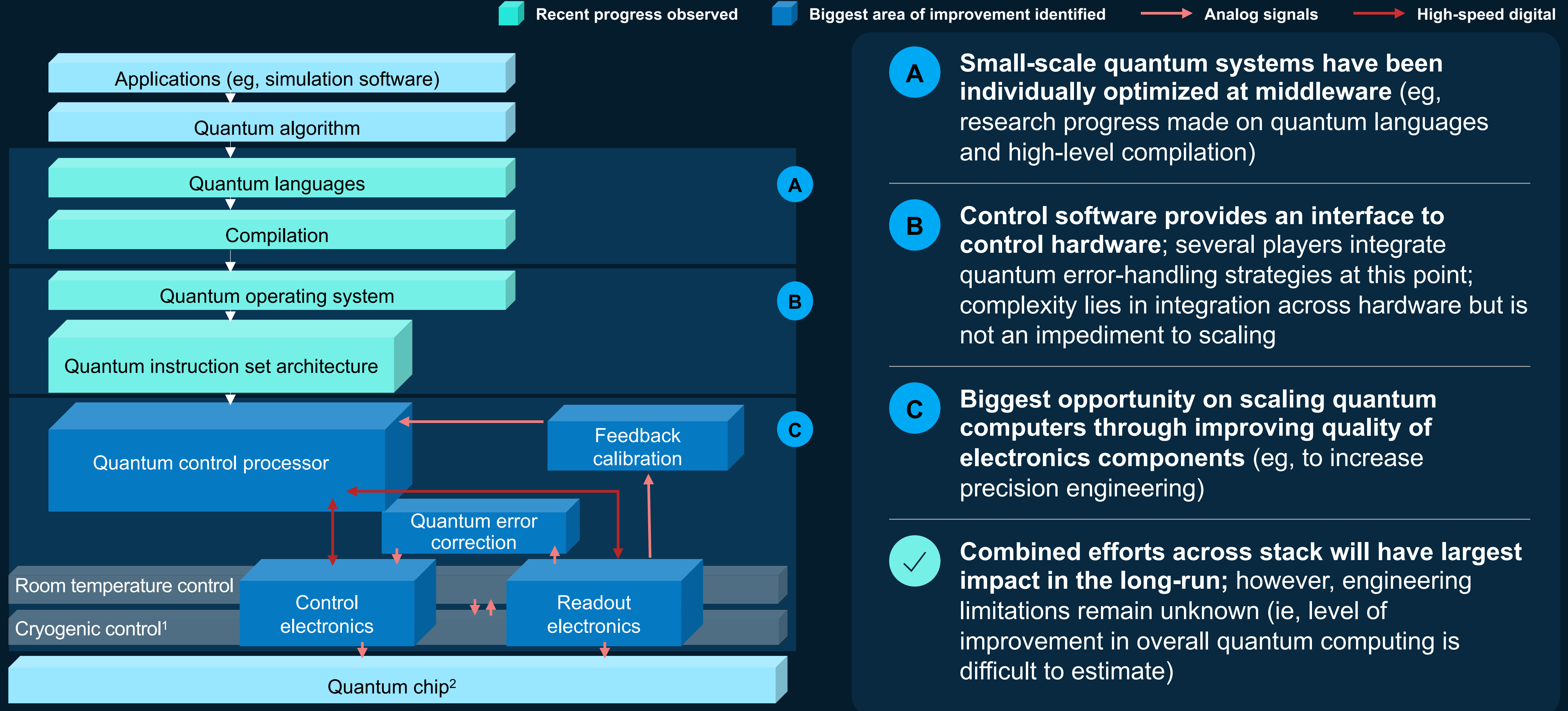
5. **Design challenge**
Number of control electronics increases with number of qubits

6. **Interconnectivity challenge**
Missing interfaces limit synchronization and throughput



Quantum control enables high-performance and large-scale quantum computing

Most value in quantum control is likely to be unlocked by focusing on low-level control components.



A **Small-scale quantum systems have been individually optimized at middleware** (eg, research progress made on quantum languages and high-level compilation)

B **Control software provides an interface to control hardware**; several players integrate quantum error-handling strategies at this point; complexity lies in integration across hardware but is not an impediment to scaling

C **Biggest opportunity on scaling quantum computers through improving quality of electronics components** (eg, to increase precision engineering)

✓ **Combined efforts across stack will have largest impact in the long-run;** however, engineering limitations remain unknown (ie, level of improvement in overall quantum computing is difficult to estimate)

[1]Only relevant for superconducting and spin-qubit technology.
[2]Some qubit technologies do not require a chip, eg, neutral-atom QC arrange qubits in array.

Source: McKinsey analysis

Benchmarking is a powerful tool for guiding companies during the transition phase of QC from research to industrialization.

Quantum computing has undergone **breakthroughs** in recent years with quantum advantage demonstrations on various machines and has started **transitioning to industrialization**

"How can quantum technology help my business?"

"There are so many different types of qubit technologies, and so many algorithms. Where should I start exploring?"

"How should I start if I want to build my own quantum team?"

A benchmark will provide **a clear guide** on:

- How different systems can **address the needs of end users, funding agencies,** and **investors**
- **Development of application, algorithm,** and **hardware**, as well as **community building**

Source: F. Arute, K. Arya et al., "Quantum supremacy using a programmable superconducting processor," *Nature*, vol. 574; L. S. Madsen, F. Laudenbach et al., "Quantum computational advantage with a programmable photonic processor," *Nature*, vol. 606

The current focus of benchmarking on hardware limits industry insight into real-world application performance.

Benchmarks can be categorized into…	Examples	Evaluation
System level Focus on the lower-level hardware and system aspects	**Quantum volume (QV) benchmark**: The largest executable circuit with equal width (number of qubits) and depth (number of circuit layers) **Circuit layer operations per second (CLOPS):** Circuit execution time on parameterized circuits, including preparation overheads	+ Provides valuable information (eg, gate fidelities, coherence times, execution speed) needed to **assess quantum hardware quality** and **to validate road maps** – **Difficult to map to application performance** (ie, no link to real-life problem or entire stack)
Algorithm level Evaluate specific, significant subroutines	**Variational quantum eigensolver (VQE)**: A quantum chemistry benchmark for noisy intermediate-scale quantum (NISQ) computers **Quantum approximate optimization algorithm (QAOA)**: evaluation of QAOA on IBM machine to solve weighted MaxCut problems and 2-satisfiability problems	+ Provides valuable information on important subroutines **to assemble/choose algorithms** addressing real-life problem – **Difficult to map to application performance** (ie, no link to real-life problem or entire stack)
Application level Assess the whole stack with interplay of different components	**Q-Score**: Hardware-agnostic, scalable benchmark measuring the maximum number of qubits to solve the MaxCut problem with QAOA **QUARK**: Hardware-agnostic, standardized benchmark including standardized data set, open-source framework for designing, implementing, executing, and analyzing benchmarks	+ **Link to application performance; easier to understand in real-life context** – **No clear business value** or **limited industries** in scope; **not digestible** for non-quantum-literate industry leaders

Numerous benchmarks have been defined and some are very vendor specific, requiring independent third-party benchmarking

Source: A. W. Cross, L. S. Bishop et al., "Validating quantum computers using randomized model circuits," *Physical Review A*, vol. 100; A. Wack, H. Paik et al, "Quality, speed, and scale: Three key attributes to measure the performance of near-term quantum computers," 2021; A. J. McCaskey, Z. P. Parks et al., "Quantum chemistry as a benchmark for near-term quantum computers," 2019

Independent, third-party reviews of use-case-based benchmarks on a holistic quantum tech stack will be necessary.

Current quantum computing benchmarks | Benchmarking scope proposed in this document

To prepare the industry and quantum community for real-world applications, we propose the establishment of an **application-based benchmark without influence from quantum stack** (hardware, software, and cloud service) **players** with:

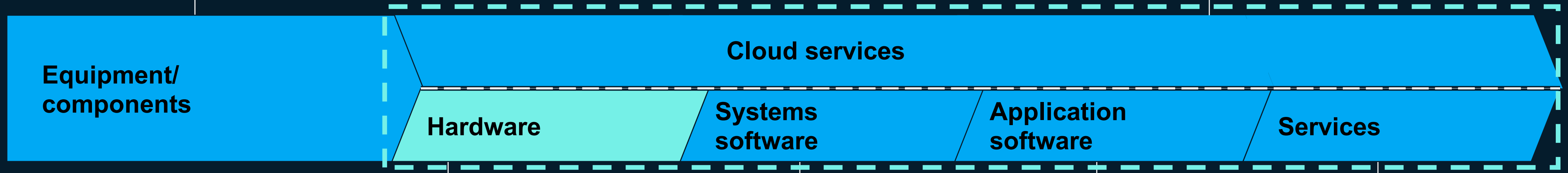
- **Standardized metrics** considering hidden costs between quantum and classical layer
- **Real-world use-case-based data sets across various industries**
- **Reproducible benchmarking methods**
- **Digestible for business leads** with little to no quantum knowledge

Description

Providers of hardware components for quantum computers (eg, semiconductors, electrical components, and dilution refrigerators)

Offering of QC capabilities either via their own cloud solution or dedicated cloud player and distribution of QC software to end users

Value chain



Description

Hardware	Systems software	Application software	Services
Manufacturing of full-scale quantum computers and simulators	Development of software that interacts with the quantum processing unit (eg, low-level programming)	Development of algorithms that run on quantum computers/ equipment and interact with the systems layer	Consulting and education services about strategic and technological aspects of quantum technologies

Shortlisted benchmarks include metrics for specific use cases and solutions, as well as for general technological aspects.

Illustrative

Benchmark area		Proposed metrics
Use case specific	**Validity**[1] If the solution conforms to all the constraint	Validity can be defined as either **the percentage of constraints the solution manages conform to,** or as **the probability to obtain the right answer**
	Execution time Time to execute the algorithm (including repetition to obtain results)	**Time-to-solution** (TTS)[1]= $T_{mapping} + T_{solver} + T_{reverseMap} + T_{processSolution}$
	Efficiency of the solution[1] Efficiency of the solution	This can be defined as, eg, the number of qubits used, the depth of the circuit or the length of the path (TSP), to **categorize the efficiency of the solution**, indicating the potential ability of the tech stack even on hardware with limited size
	Cost Financial cost per job or energy cost	**Current financial cost** per job for given tech stack with **forward-looking predictions** based on their scalability and energy cost
General	**Key hardware performance** Including noise level to execute the whole usecase	This includes: a) high-fidelity two-qubit gates at scale; b) gate speed; c) multi-qubit networking; d) individual qubit control at scale; e) cooling power/environment control; and f) manufacturability
	User-friendliness Ease to learn, expressibility, modulation level and transparency (open-source)	**Questionnaire** to quantum developers to rate following areas: • **Ease to learn:** Separately for developers who have 1) no prior quantum experience; 2) no prior coding experience; or 3) neither • **Expressibility**: The range of problems archetypes can be addressed on the given stack • **Modulation level**: How packaged important subroutines are on the given tech stack • **Transparency**: If all the functions/packages are well documented on open-source platforms

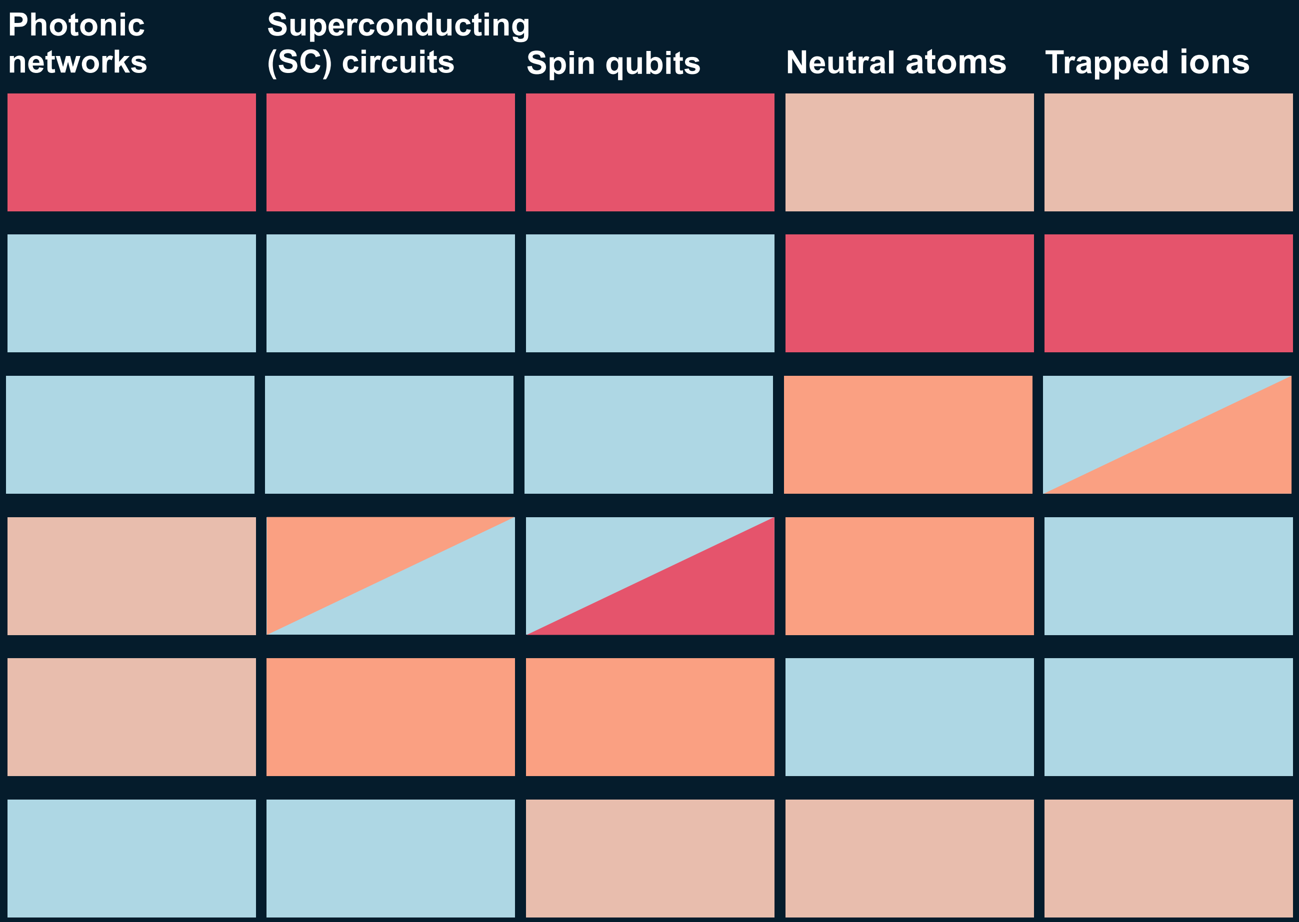
[1]Finžgar, Jernej Rudi et al. "QUARK: A framework for quantum computing application benchmarking," 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), IEEE, 2022.

Source: McKinsey analysis

Hardware benchmarking of qubit technologies shows a number of engineering challenges to achieving full-scale fault-tolerant QCs.

Major challenge to reach full-scale fault-tolerant QC — Ready for full-scale, fault-tolerant QC

Long-term scalability across key technological challenges per modality[1]



Challenge

1. **Two-qubit gate fidelity at scale[2]**
Gate fidelity for two-qubit operations[3] for systems at scale: fidelity of one logical qubit; number of logical qubits needed for full-scale fault-tolerance

2. **Speed of computation**
Two-qubit gate operation speed; speed of all other processes required to run a computation

3. **Multi-qubit networking**
Chip-to-chip connectivity; ability to perform two-qubit gates[1] across chips (including speed considerations)

4. **Individual qubit control at scale**
Ability to precisely control any chosen individual qubit without disrupting other parts of the QC

5. **Cooling power/environmental control**
Ability to cool down millions of qubits and their control electronics to a stable, required temperature

6. **Manufacturability**
Ability of automated production of qubits at scale, including characterization, screening, and validation of billions of components

[1]The long-term here is defined as achieving thousands of logical qubits to produce a universal fault-tolerant quantum computer; in the short-term, colors would be different, eg, trapped ions and neutral atoms scalability to ~10k high-fidelity physical qubits easier than for other modalities; however, significant challenges arise for these modalities when scaling beyond this size because of speed of computation (and laser power plus connectivity for neutral atoms).
[2]Scalability of fidelity with system size is challenging to assess given lack of transparency, internal benchmarks, and error models that are not publicly disclosed by hardware players.
[3]Qubit operations can be reduced to a universal set of two-qubit gates.

Source: McKinsey analysis

Leading qubit technologies are on track to build a scalable universal quantum computer.

Not exhaustive

Technology	Photonic networks	Superconducting (SC) circuits	Spin qubits[1]	Neutral atoms	Trapped ions
Qubit description	Occupation of a photonic waveguide	Difference in energy states of Cooper pairs between two sides of a Josephson tunnel junction	Electron spins of different materials (eg, an electron trapped within a silicon quantum dot or a color center in an insulator) controlled by laser light or microwave radiation	Internal energy levels of neutral atoms trapped by laser fields	Internal energy levels of ions trapped by electromagnetic fields
Physical qubit count[2]	**216** Xanadu **256** PsiQuantum	**1,121** IBM **84** Rigetti **127** Google **64** Fujitsu **64** Microsoft **16** Alice & Bob	**12** Intel	**256** QuEra **1,180** Atom Computing **1,600** Infleqtion	**36** IonQ **20** Alpine Quantum Technologies

Example road map[2]

IBM

	2023	2024	2025	2029	2033
Logical qubits		156	156	200	2,000
Physical qubits	1,121	1,386+	4,158+		

Error corrected (2029)

Google

	2023	2025+	n/a
Logical qubits	10^2	10^3	10^6

Error corrected (n/a)

QuEra

	2023	2024	2025	2033
Logical qubits		10	30	100
Physical qubits	256	>256	>3,000	>10,000

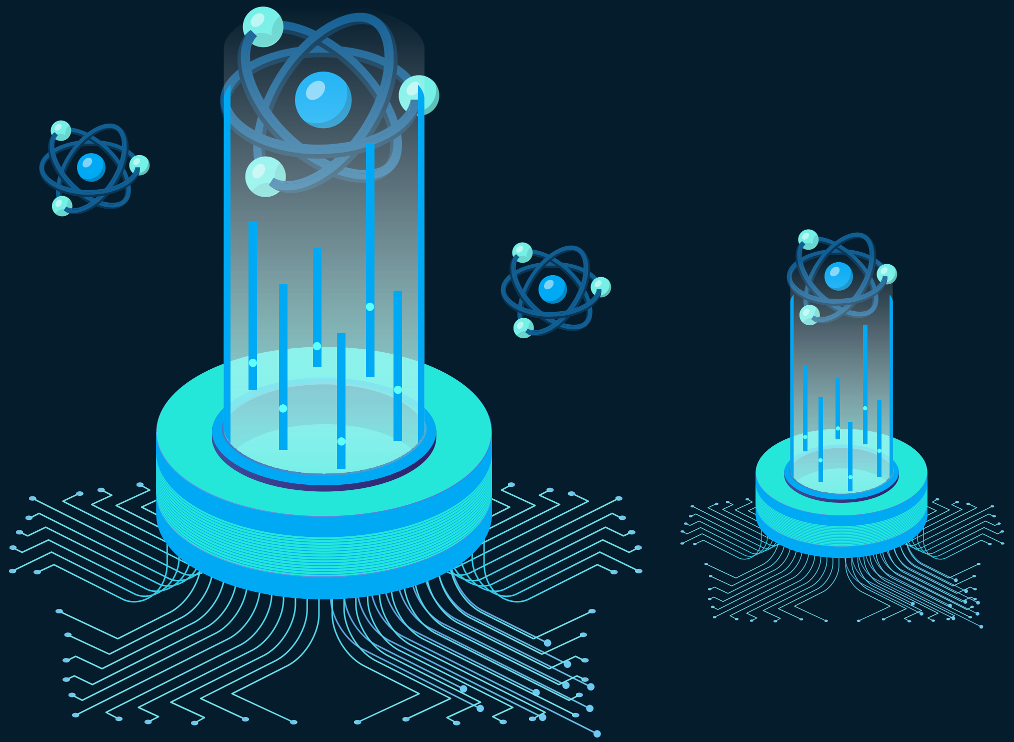
Infleqtion

	2024	2026	2028
Logical qubits	2	>10	>100
Physical qubits	1,600	8,000	40,000

Error corrected (2026)

[1]We examine electron spins in silicon quantum dots, as other spin qubits are generally not considered for applications in quantum computing.
[2]Qubit counts and road maps are selected based on available public announcements and available information as of March 2024.

Source: Publicly available data



Quantum communication

In the near term, QComm is expected to continue producing technological advancements and attracting commercial interest.

Non-exhaustive

Commercial and policy updates

- Hyperscalers (eg, AWS), telcos (eg, Orange), and quantum key distribution (QKD) companies (eg, Toshiba Europe) continue to prototype and deploy metro-scale QKD networks with clients
- Start-ups continue to improve the performance of QKD systems and protocols (eg, range, transmission rate)
- Post-quantum cryptography (PQC) continues to gain traction as technology companies roll out PQC deployments (eg, Apple's PQ3 for iMessage, Vodafone, and SandboxAQ for quantum-safe VPN)
- Governments and organizations worldwide begin establishing initiatives regarding post-quantum cryptography (eg, US CISA[1] announces PQC Initiative, part of NATO's inaugural quantum strategy)

Technology development

- NIST released draft standards for three of the four PQC algorithms selected in 2022
- Research continues to create quantum memories based on solid-state spins, rare earth ions, and atomic vapors
- Quantum repeaters are demonstrated using trapped ions operating at telecom wavelengths
- QKD performance improvements (eg, longer range) are achieved via more sophisticated approaches (eg, continuous-variable QKD)
- Project Petrus is launched for the deployment of a secure quantum communication infrastructure across the whole European Union

Ecosystems and hubs

US: Boston-Area Quantum Network, Chicago Quantum Network
EU: Italian Quantum Backbone, Madrid Quantum Communication Infrastructure, London Quantum Secured Metro Network
Asia: Beijing-Shanghai Backbone Network (BSBN), Singapore National Quantum-Safe Network, Tokyo QKD Network

[1] Cybersecurity & Infrastructure Security Agency.

Source: McKinsey analysis

QComm adoption is expected to accelerate over the coming decade as quantum computing cybersecurity risks increase.

Milestones and technical enablers for secure quantum communication

Illustrative

Milestones

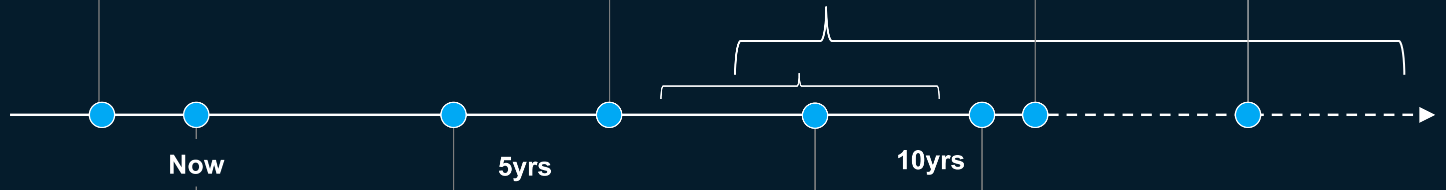
Short-distance secure QComm
Secure quantum communication <500km to allow transmission of highly sensitive data without risk of interception

Quantum networks connecting cities
Establish secure quantum networks between distant cities

Quantum internet
Secure quantum internet merging classical and quantum communication

Mobile quantum networks (not within foreseeable future)
Quantum communi-cation through mobile phone networks

Key applications
Applications like quantum credit cards emerge



Technical enablers

Quantum satellites
Provide entangled photons

PoC quantum repeaters
Amplify signal and reduce error rates to enable communication over long distances

Quantum communication software stack
Software protocols to process incoming and outgoing signals

Commercial quantum repeaters
Quantum repeaters with encryption and memory

Quantum computing development

Pre-QC era

There **may not be a clear turning point** when the **pre-QC era switches to the post-QC era**
(eg, nations starting usage of full-scale QC without making this public)

Post-QC era

Key takeaways

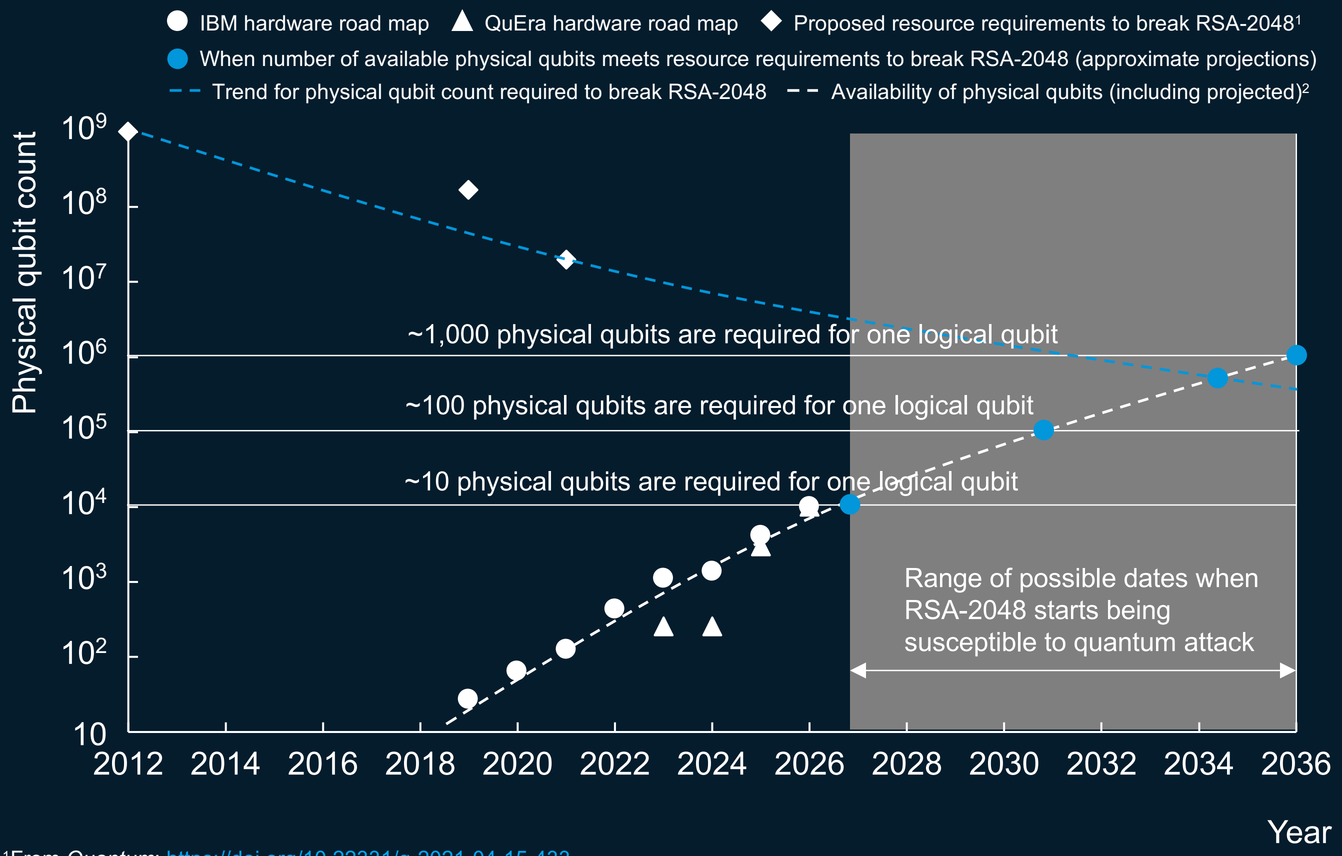
- **Short-distance secure quantum is available today**; front-runners have started experimenting with implementation.
- **Long-distance communication requires quantum repeaters**. As all core elements of this technology are available today, field-deployed demonstrations are expected in the next few years.
- **Quantum encryption likely sees wider adoption in next decade**, especially driven through telecommunications, finance/banking, and defense.
- Once **quantum computers mature**, **quantum communication will enable connectivity** between processors and data centers for parallel quantum computing.

Source: European Quantum Manifesto; McKinsey analysis

Timelines for susceptibility to quantum attack depend on qubit hardware development and implementation.

Illustrative

Quantum resource availability and requirements by year, 2012–2036



The date by which commonly used cryptosystems (eg, RSA, ECC) are susceptible to quantum attack depends on the availability of quantum resources (eg, number of physical qubits) and qubit implementations (eg, number of physical qubits needed to operate a logical qubit).[3]

To break RSA-2048 in reasonable time (~days), schemes requiring ~10^3–10^4 logical qubits have been proposed; ~10^3 physical qubits are required for one logical qubit, though more recently announced techniques reduce the number of physical qubits per logical qubit to 10–100, which is an active area of research by companies such as Alice & Bob, AWS, IBM, and QuEra.

Decrypting RSA-2048 would then require at minimum ~10^4 and up to ~10^7 physical qubit,s which provide the timeline range based on the road maps for availability of physical qubits by major QC players.

[1]From *Quantum*: https://doi.org/10.22331/q-2021-04-15-433.
[2]Historical for pre-year 2024, projected for post-2024.
[3]Not considering harvest now, decrypt later attacks that have an earlier time horizon but actual decryption date.

Source: Alice & Bob; Google; IBM; Microsoft; QuEra; McKinsey analysis

Despite technological advancements and anticipated need for QComm, 2023 saw few new start-ups focused on the field.

Number of QComm start-ups by country

Not exhaustive

+ indicates change since 2022

Country	2023	2022	2021
United States	20	20	19
China[1]	16	16	16
United Kingdom	14	14	14
Canada	9	9	8
France	4	4	4
Germany	4	3	3
Netherlands	3	3	3
Switzerland	3	3	3
Singapore	3	3	3
Spain	3	3	2
Japan[1]	2	2	2
Poland	2	2	2

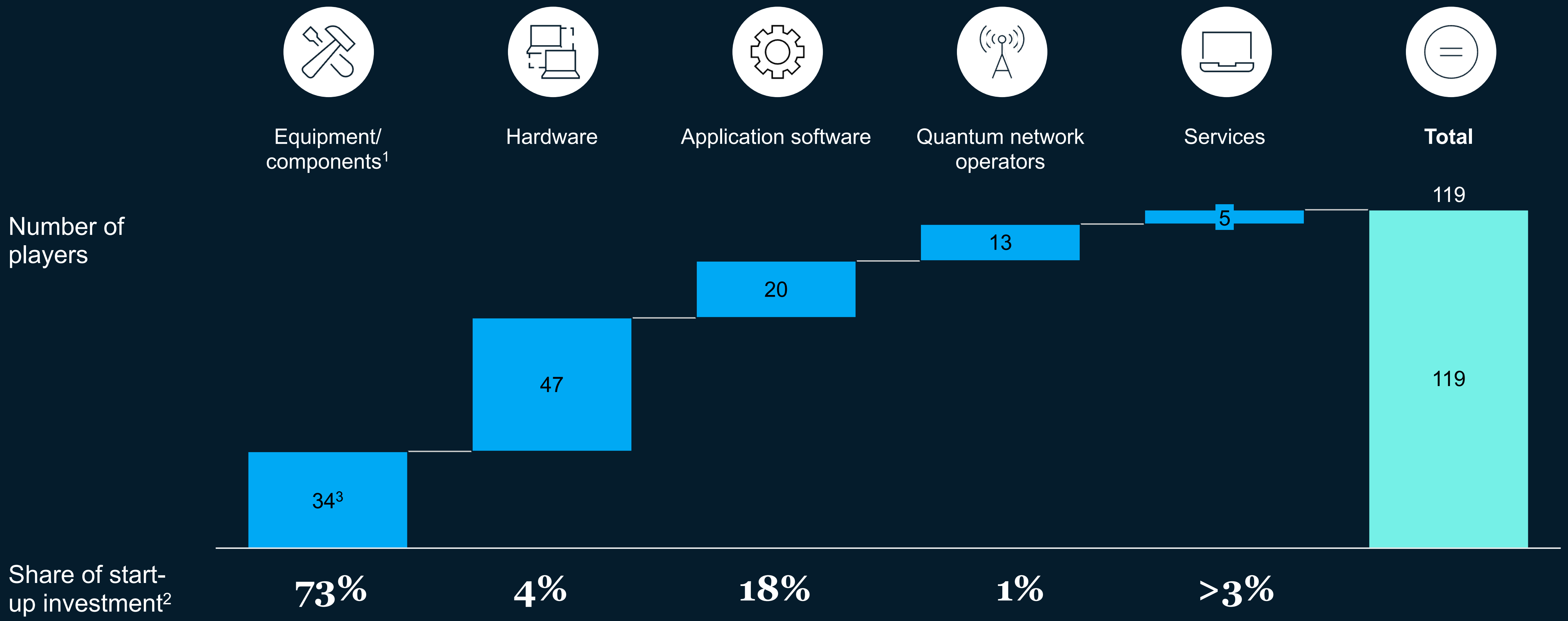
Country	2023		2022	2021
Australia	2		2	2
India	2		2	2
Russia	2		2	1
Colombia	1		1	1
Finland	1		1	1
Israel	1		1	1
Bulgaria	1		1	1
South Korea	1		1	1
Scotland	1		1	1
Liechtenstein	1		1	0
Portugal	1	+1	0	0
Grand total	**96**	+1	**95**	**90**

[1]There is limited transparency on commercial activity in China and to a lesser extent for Japan. We think Chinese activity in quantum technologies is primarily through government-funded research institutions.

Source: CapitalIQ; Crunchbase; PitchBook; Quantum Computing Report; expert interviews

Though QComm equipment start-ups make up about a third of the field's new businesses, they garner the most funding.

Number of QComm players by value-chain segment[1]



[1]Includes start-ups and incumbents that develop or offer QComm products; see methodology (p. 102) for details.
[2]Based on public investments in start-ups recorded on PitchBook and announced in the press; excludes investments in internal QT departments or projects by incumbents; actual investment is likely higher.
[3]There are more than 100 total suppliers; however, only 34 are start-ups specific to quantum communication.

Source: CapitalIQ; Crunchbase; PitchBook; Quantum Computing Report; McKinsey analysis

Quantum sensing

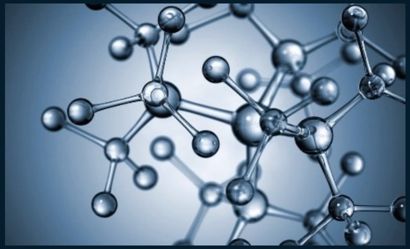
QS enables new applications through reliable measurements that are orders of magnitude more sensitive than classical sensors.

Not exhaustive

Applications

Next step: Identification of economically viable use cases vs conventional alternatives

Bioimaging, including brain scans, imaging of protein structures, and real-time metabolic processes

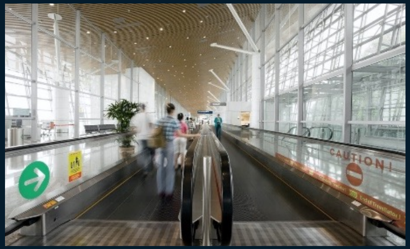


Imaging of molecular structures (spectroscopy)

Signal receivers and amplifiers for radar communication

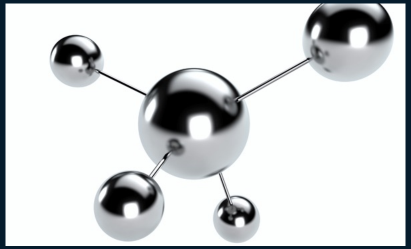
Calibration of electrical standards for new technologies (eg, 5G, 6G)

Precise atomic clocks for high-accuracy GPS navigation



Navigation inside buildings and underground

Environmental monitoring (eg, prediction of volcano outbursts)



Fundamental research (eg, high-energy physics)

Quantum sensing is the application of **quantum metrology** in practical settings.

*"You have to do very accurate measurements to compare values; that's **metrology**. When you then put this technique into instruments and place them in the field, you build up a **sensor**."*

—Professor of Quantum Communication, Computing & Measurement at Boston University

The increased sensitivity of QS can enable new applications.

Key benefits of quantum vs classical sensors

Higher precision

The enhanced sensitivity of quantum systems to the outside world can be leveraged to reach a **higher sensitivity**

Enhanced access

Quantum sensors provide **new access (**eg, extremely small ranges in size, high resolution, or inaccessible locations)

Measured properties

- Magnetic field
- Temperature
- Time
- Rotation
- Force
- Pressure
- Electric field

Source: McKinsey analysis

New QS applications will impact a number of industries.

Industry	Oil & gas	Automotive & assembly	Aerospace & defense	Advanced electronics & semiconductors	Medtech	Media/enter-tainment	Insurance	Public sector
Monitoring	Seismic monitoring Pipeline properties monitoring for predictive maintenance	Production-line optimization (eg, positioning) and quality assurance		Production-line optimization (eg, positioning) and quality assurance Battery-life improvement and predictive maintenance			Weather predictions for climate models	Public safety environmental monitoring (eg, volcano prediction, seismic disturbances, weather predictions)
Imaging					Cardiovascular irregularities (MCG), brain abnormalities (MEG)	Gaming interfaces, BCI		
Navigation		Precise atomic clocks for high-accuracy GPS navigation	Precise atomic clocks for high-accuracy GPS navigation					
Identifica-tion	Identification of natural resources	Faulty part identification in production		Faulty-part detection in microelectronics				

Source: McKinsey analysis

Recent advances showcase the impact potential of QS.

Not exhaustive

Industry adoption

- April 2023, quantum sensing company QUSPIN releases a new integrated optically pumped magnetometer (OPM) for biomagnetic applications. The sensitivity is one of the first OPMs on par (~10 fT $Hz^{-1/2}$)[1] with SQUID[2] devices (but, critically, does not require operation at cryogenic temperatures)
- February 2023, US Air Force awards SandboxAQ contract for development of a quantum sensing alternative to GPS[3]
- October 2023, Bosch Quantum Sensing is targeting miniaturization of quantum sensors and is working to integrate quantum sensors onto chips[4]
- January 2024, Q-CTRL announced a partnership with USGS aiming to use QS techniques like quantum magnetometry for geological sciences, incl. earlier detection of hazards, novel methods to monitor water assets, and more[5]

Academic progress

- February 2024, MIT researchers developed a new technique to control a greater number of microscopic defects inside diamonds to create "qubits" that can be used for quantum sensing[6]
- August 2023, National Science Foundation announces $29M investment in 18 teams across US universities: "Collectively, the teams will conduct a broad range of exploratory research activities, from measuring the height and density of mountains with an ultraprecise atomic clock to revealing the inner functions of living cells with quantum-entangled particles of light"[7]
- October 2023, researchers from the Niels Bohr Institute (NBI), University of Copenhagen, developed a novel method to detect and mitigate "quantum noise" enabling higher precision for quantum sensors[8]
- October 2023, UC Berkeley researchers demonstrated a new 3D printing technique for quantum sensors enabling incorporation into a variety of systems (eg, electronics or biological)[9]

[1]QZFM Gen-3, QUSPIN.
[2]Superconducting quantum interference devices.
[3]IOT World Today, "US Air Force Awards SandboxAQ Quantum Navigation Research Contract."
[4]Bosch, "Quantum technologies: Bosch aims to use sensors to take a leading position."
[5]The Quantum Insider, "Q-CTRL partners with USGS to pioneer quantum sensing and computing applications."
[6]A. Ungar et. al., PRX Quantum 5, 010321 (2024).
[7]NSF, "Quantum-scale sensors to yield human-scale benefits with new backing from NSF."
[8]J. Jia et. al. *Nature Communications,* 14, 6396 (2023).
[9]B.W. Blankenship et. al., *Nano Letters*, 23, 20, 9272–9279 (2023).

The promise of QS has not yet been reflected in start-up activity.

Number of QS start-ups by country

Not exhaustive

+ indicates change since 2022

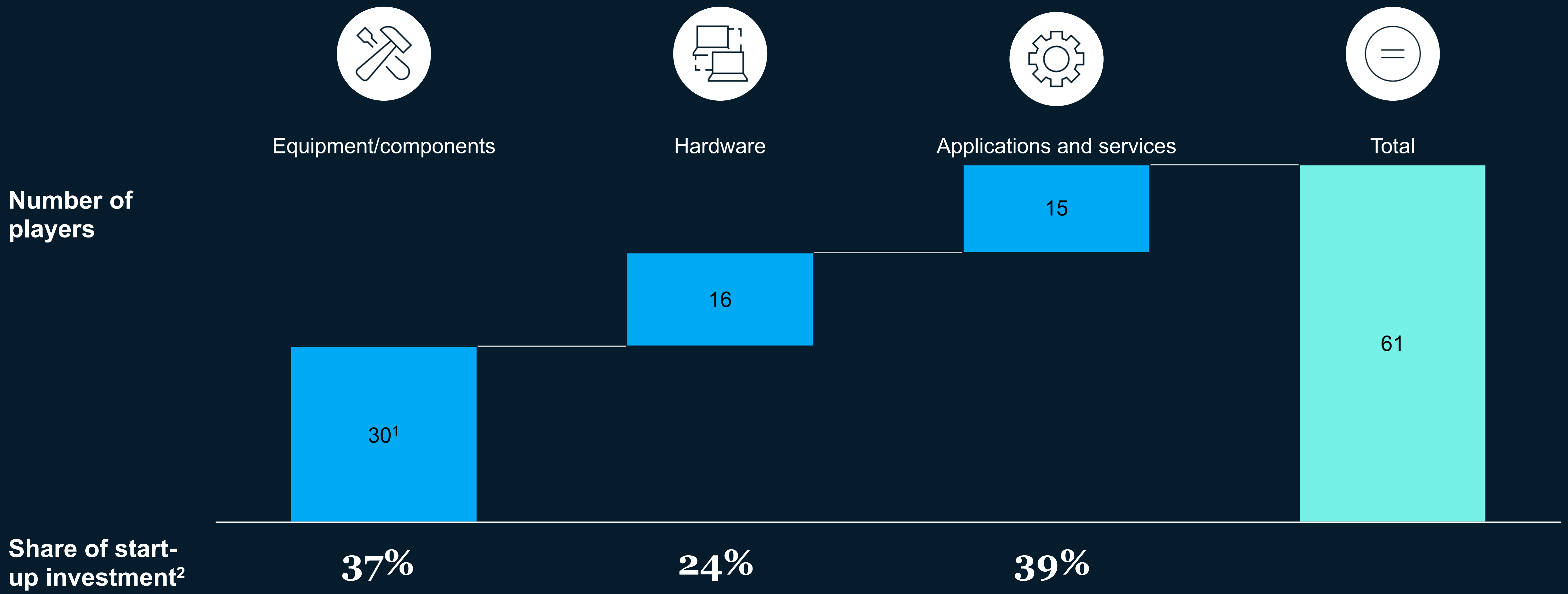
Country	2023		2022	2021
United States	15	+1	14	13
Switzerland	5		5	5
Germany	5		5	4
United Kingdom	5	+1	4	4
France	4		4	4
China[1]	3		3	3
Netherlands	2		2	2
Denmark	2		2	2
Australia	1		1	1
Canada	1		1	1
Finland	1		1	1
Japan[1]	1		1	1
Singapore	1		1	1
Sweden	1		1	1
Turkey	1		1	1
Grand total	**48**	+2	**46**	**44**

[1]There is limited transparency on commercial activity in China and to a lesser extent for Japan. We think Chinese activity in quantum technologies is primarily through government-funded research institutions.

Source: CapitalIQ; Crunchbase; PitchBook; Quantum Computing Report; McKinsey analysis

Half of QS players focus on components, yet start-up investments focus more on hardware and applications/services development.

Number of QS players by value-chain segment



[1]There are more than 100 total suppliers; however, only 30 are start-ups specific to quantum sensing.
[2]Based on public investments in start-ups recorded on PitchBook and announced in the press; excludes investments in internal QT departments or projects by incumbents; actual investment is likely higher.

Source: CapitalIQ; Crunchbase; PitchBook; Quantum Computing Report; McKinsey analysis

Quantum and AI

Generative AI

Gen AI is set to unlock

$2.6T–$4.4T

annually across 63 new use cases when applied across industries[1]

Quantum computing

Quantum computing can generate

$0.9T–$2T

in value by 2035 across chemicals, life sciences, finance, and mobility

Both gen AI and quantum computing have tremendous potential to unlock value

[1] "The economic potential of generative AI: The next productivity frontier," McKinsey, June 14, 2023.

Training of gen AI is currently constrained by three main issues that quantum computing could help resolve

Memory size

As gen AI models get larger, the memory in classical GPUs will be insufficient to store the models

Memory wall

As gen AI models become increasingly complex, loading data from memory will become slower, yielding long idling times for processors

Compute power

The required compute power to train the largest gen AI models grows exponentially; classical compute power cannot match this growth and is insufficient

Gen AI can help speed up development of quantum computing hardware and software

Hardware

Each qubit modality has its unique challenges that need to be solved to create a universal fault-tolerant quantum computer

Software

Developing optimized software for quantum computers requires deep technical knowledge of the underlying system, which many coders do not have

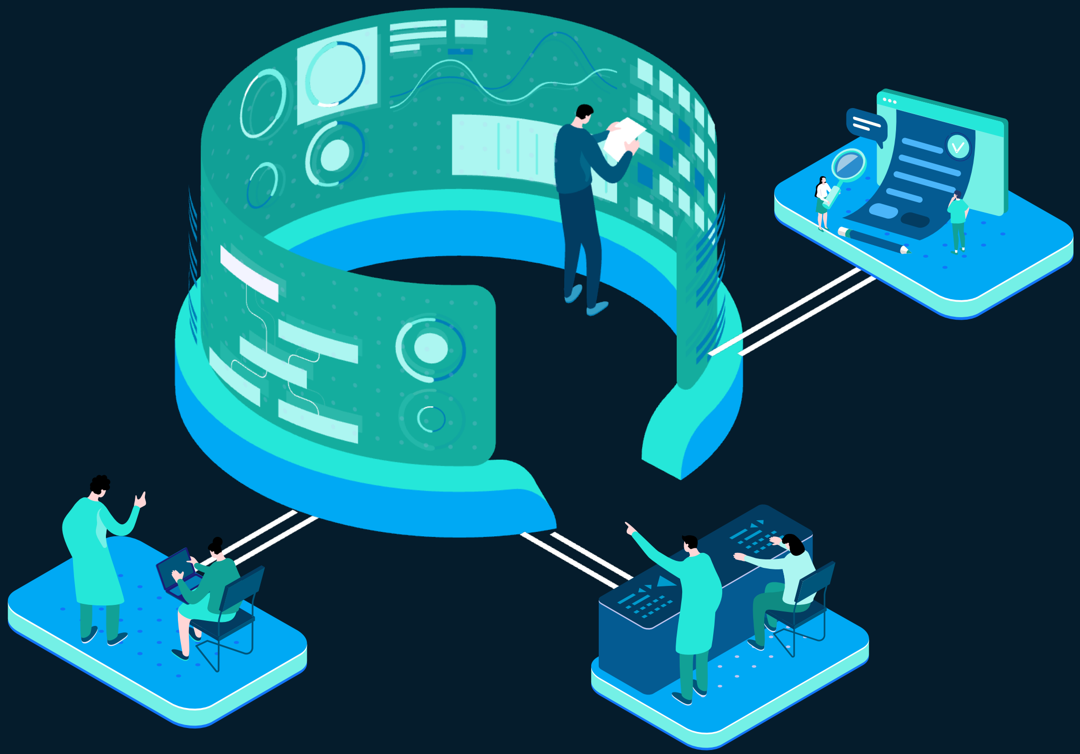
Integration

Hybrid systems will be used whenever it is beneficial for the outcome to run parts of the code on a quantum machine

Quantum computing can help provide compute power needed for gen AI training

Gen AI can help speed up the development and testing time of quantum systems

Connecting generative AI and quantum computing could create an impact larger than the sum of the two technologies



Methodology and acknowledgments

Methodology

Quantum technology investments, market sizing, and player landscape

- Investments in start-ups have been extracted from PitchBook and analyzed by McKinsey
- Market sizes have been calculated across three scenarios (low, base, high) that consider different hypotheses for the spread of use of QC, QComm, and QS, as well as the speed at which technological challenges are resolved
- To obtain the QT player landscape, we considered the following:
  - — Start-ups: founded in the past 25 years, with estimated revenues below $200 million
  - — Incumbent companies: companies with revenues above $200 million
  - — Components manufacturers are considered if they develop components specifically for QT; general technology components suppliers are excluded
  - — Hardware manufacturers are considered if they have already demonstrated the creation of a quantum computer or have announced efforts in this direction
  - — Telecommunications companies are considered if they invest in QComm to become a quantum network operator
  - — Relevant general technology components suppliers are included in the ecosystem but not in the overall count of QT players; the same holds for quantum media companies and quantum education providers

Meet the team behind the Quantum Technology Monitor

This research was conducted in collaboration with the McKinsey Technology Council, which brings together a global group of scientists, entrepreneurs, researchers, and business leaders. Together, they research, debate, inform, and advise, helping executives from all sectors navigate the fast-changing technology landscape.

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