McKinsey & Company

Quantum Technology Monitor

April 2023

What can you find in this report?

Continuously evolving overview of the **global quantum technology (QT) player and investment space,** updated annually, including quantum computing (QC), quantum communications (QComms), and quantum sensing (QS); see page 52 for definitions of these areas

Dynamic overview of the **maturity of the QT ecosystem and the use of QT in the broader industry context,** based on the current application of the technology and patents

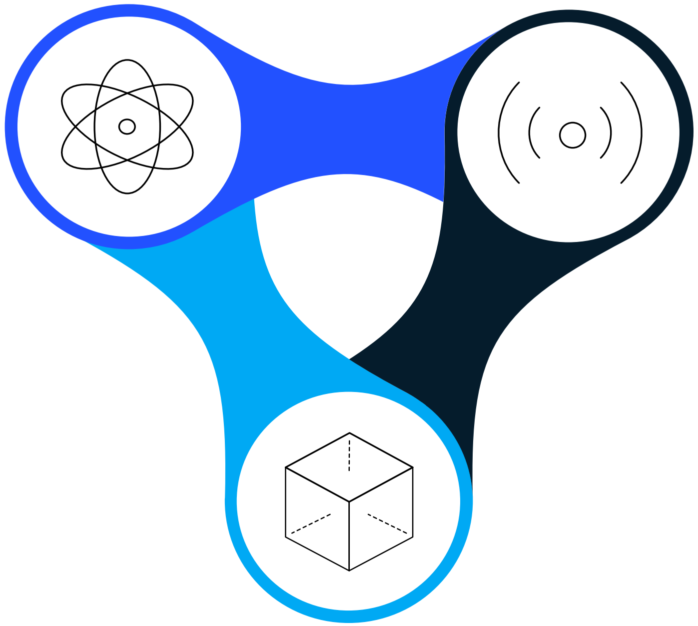
Definitive and exhaustive list of the start-up, investment, and economic activities in the QT realm

New additions to the Monitor

- Improved investment insights (pp 7–17)
- Enhanced perspective on quantum technology (QT) in China and Japan (pp 16–17)
- Deep dive on the quantum software ecosystem (pp 26–27)
- Refreshed use-case value matrix of quantum computing (QC) by industry (p 30)
- Deep dive on the quantum sensing (QS) ecosystem (pp 40–43)

Note: The Quantum Technology Monitor 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.

Definitions: Quantum technology encompasses three subfields: computing, communications, and sensing.



- **Quantum computing (QC)** is a new technology for computation, which leverages the laws of quantum mechanics to provide exponential performance improvement for some applications and to potentially enable completely new territories of computing. Some of the early quantum hardware products are special-purpose quantum computers, also called quantum simulators.
- **Quantum communications (QComms)** is the secure transfer of quantum information across space.[1] It could ensure security of communications, enabled by quantum cryptography, even in the face of unlimited (quantum) computing power.[2]
- **Quantum sensing (QS)** is the new generation of sensors built from quantum systems. It could provide measurements of various quantities (eg, gravity, time, electromagnetism) that are orders of magnitude more sensitive than classical sensors.

[1]Quantum information is information stored 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. However, early implementations have been shown to have some weaknesses.

Source: Expert interviews

The quantum technology ecosystem in 2023

Summary of Quantum Technology Monitor findings

$106B

potential quantum technology market size by 2040[1]

350

start-ups in the ecosystem[2]

$34B total government investment announced

Quantum computing

$9B–$93B

estimated market size by 2040

$5.4B invested as of Dec 2022

223 start-ups as of Dec 2022

Quantum communications

$1B–$7B

estimated market size by 2040

$1.0B invested as of Dec 2022

72 start-ups as of Dec 2022

Quantum sensing

$1B–$6B

estimated market size by 2040

$0.4B invested as of Dec 2022

23 start-ups as of Dec 2022

Potential economic value from quantum computing

$620B–$1,270B

across four industries by 2035: chemicals, life sciences, finance, and automotive[3]

Quantum-capable talent

50 QT master's degree programs

180 universities with QT research groups

Scientific progress

1,589 QT-related patents granted in 2022

44,155 QT-related publications in 2022

[1] The potential 2040 market size is a sum of the upper ranges across quantum computing, quantum communications, and quantum sensing.
[2] Total includes 32 companies that do two or more quantum technologies simultaneously.
[3] Economic value is defined as the additional revenue and saved costs that the application of quantum computing can unlock. These four industries are the most likely to realize this value earlier than other industries; therefore, they are examined in more depth.

Executive summary

Investment and ecosystem

— Total annual QT start-up investment hit a new high ($2.35 billion), though growth was only 1% YoY

— About two-thirds, or 68 percent, of all QT start-up investments since 2001 occurred in 2021 and 2022

— With 350 start-ups in the QT ecosystem, the rate of start-up creation slowed and has not kept pace with investments, indicating that investments are going into established start-ups rather than toward new ideas; information that Series A and B start-ups have attracted particular attention in 2022 supports that statement

— 2022 was a year of big deals: four of the ten biggest QT investment deals since 2001 were closed in 2022: SandboxAQ ($500 million), Rigetti ($345 million in a SPAC deal), D-Wave ($300 million in a SPAC deal), and Origin Quantum ($149 million)

— Public investments continue: the United States, the European Union, and Canada committed an additional $1.8 billion, $1.2 billion, and $0.1 billion, respectively

Research and technology progress

— The 2022 Nobel Prize in Physics was awarded to quantum-entanglement pioneers Alain Aspect, John Clauser, and Anton Zeilinger

— IBM unveiled the Osprey (433 qubits) and updated its road map to develop a 4,000+ qubit processor in 2025

— Xanadu demonstrated quantum advantage for GBS[1] using its photonic quantum computer

— Patent issuance and publishing dropped in 2022, potentially indicating that the easiest challenges have already been addressed; 1,589 QT-related patents were granted in 2022, 61 percent less than in 2021, and 44,155 QT-related papers were published in 2022, 5 percent less than 2021

Projected economic value

— The potential economic value of QC use cases in the financial industry has grown to between $394 billion and $700 billion, with corporate banking, risk, and cybersecurity offering the most valuable use cases

Quantum talent

— The talent gap for QT jobs narrowed, yet remains wide; approximately one in two jobs remained vacant in 2022, compared to one in three in 2021

— The number of universities offering official master's degrees in QT nearly doubled in 2022, from 29 to 50

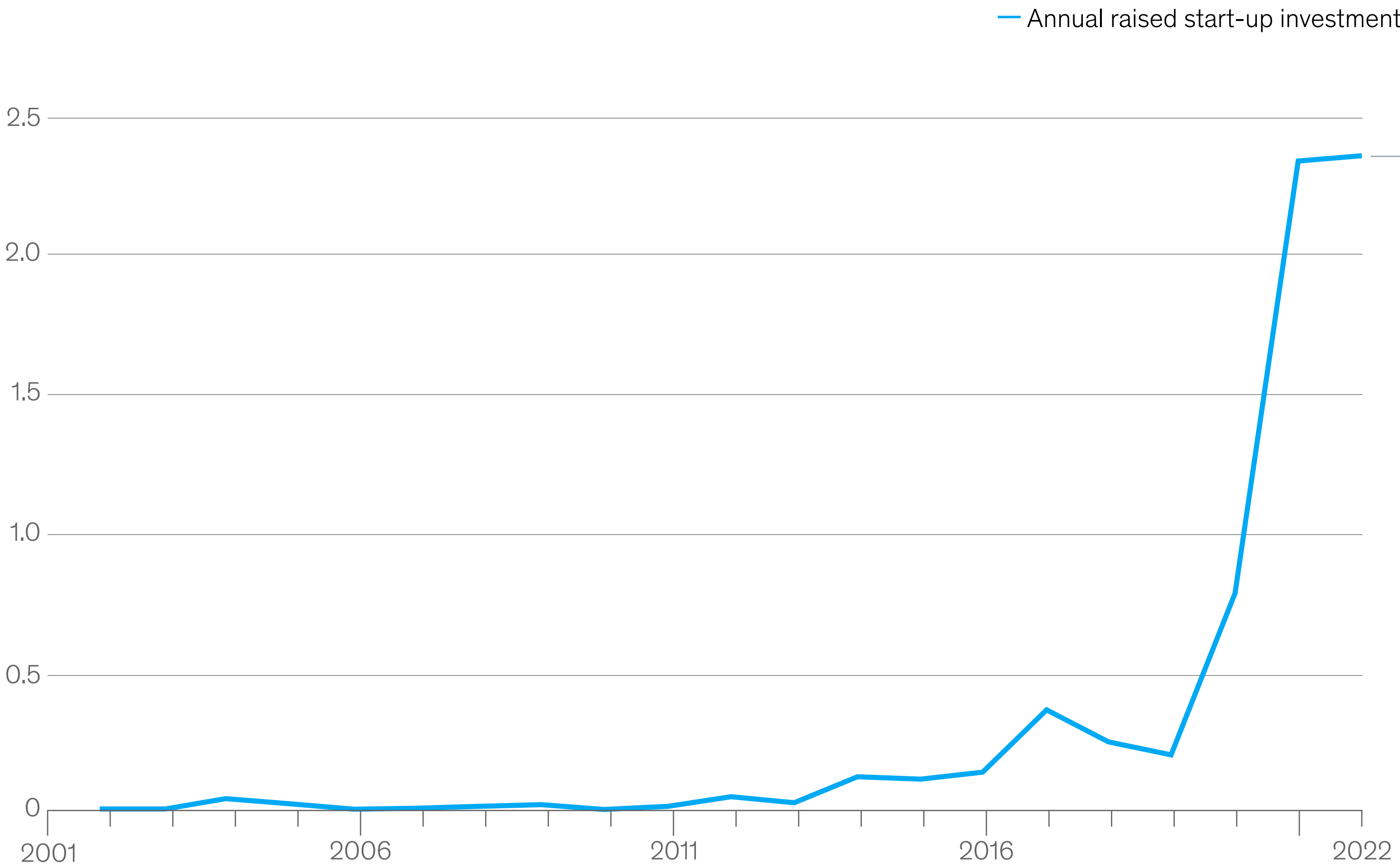
[1] Gaussian boson sampling: a probability-distribution-sampling problem; quantum advantage has previously been demonstrated for this problem by Google and researchers from the Chinese Academy of Sciences.

Contents

Quantum technology investment landscape

Total annual QT start-up investment hit the highest level of all-time, though it grew only 1 percent year over year.

Volume of raised investment in the indicated year,[1] $ billion



$2.35B

75%

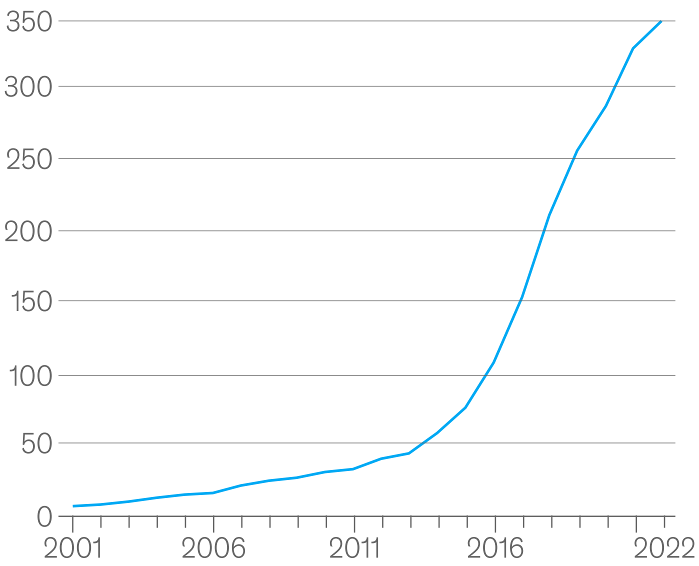
of investment goes toward quantum computing players

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

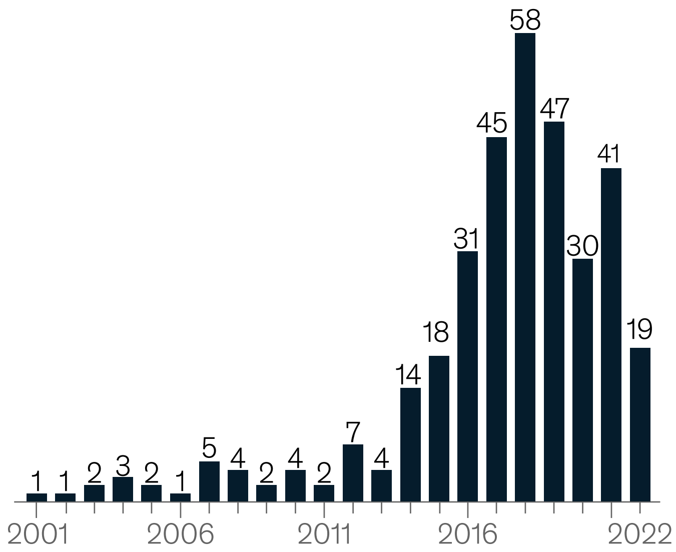
Source: PitchBook

Despite record investment, the rate of QT start-up creation slowed in 2022.

Cumulative number of QT start-ups founded



Number of QT start-ups founded per year



Potential hypotheses on the causes of the slowdown:

- **Lack of talent:** Most experienced specialists (generally academics with research focus in QT) already work in a start-up
- **Few working use cases:** Application start-up creation is limited because working use cases are very limited or not sufficiently developed for commercial implementation (eg, in QS)
- **Investor trends:** Investors prefer to invest in scale-ups and later-stage start-ups, limiting capital for a company that is just starting

80%

of start-ups founded in past 3 years are in QC space

Source: Crunchbase; PitchBook

The year featured comparatively big deals, with four new entrants into the top ten.

Top 10 venture capital/private equity investments in QT start-ups of all time, by deal size (descending)

New entrants | Quantum computing | Quantum communications | Quantum sensing

Company	Country	Tech	Segment	Deal size, $ million	Deal year
SandboxAQ	United States	Quantum sensing, Quantum communications, Quantum computing	Application software	500	2022
PsiQuantum	United States	Quantum computing	Hardware manufacturing	450	2021
IonQ	United States	Quantum computing	Hardware manufacturing	350	2021
Rigetti Computing	United States	Quantum computing	Hardware manufacturing	345	2022
Arqit	United Kingdom	Quantum communications	Hardware manufacturing	345	2021
IonQ	United States	Quantum computing	Hardware manufacturing	300	2021
Quantinuum	United Kingdom	Quantum computing	Vertically integrated[1]	300	2021
D-Wave Systems	Canada	Quantum computing	Hardware manufacturing	300	2022
PsiQuantum	United States	Quantum computing	Hardware manufacturing	230	2020
Origin Quantum	China	Quantum computing	Hardware manufacturing	149	2022

[1]Quantinuum crosses all segments, from hardware to services and software, as it was created in a merger between Honeywell Quantum Solutions (hardware manufacturer) and Cambridge Quantum Computing (systems and application software).

Source: Crunchbase; PitchBook

Seven out of ten deals in 2022 were valued at more than $100 million.

Top 10 venture capital/private equity investments in QT start-ups in 2022, by deal size (descending)

Quantum computing | Quantum communications | Quantum sensing

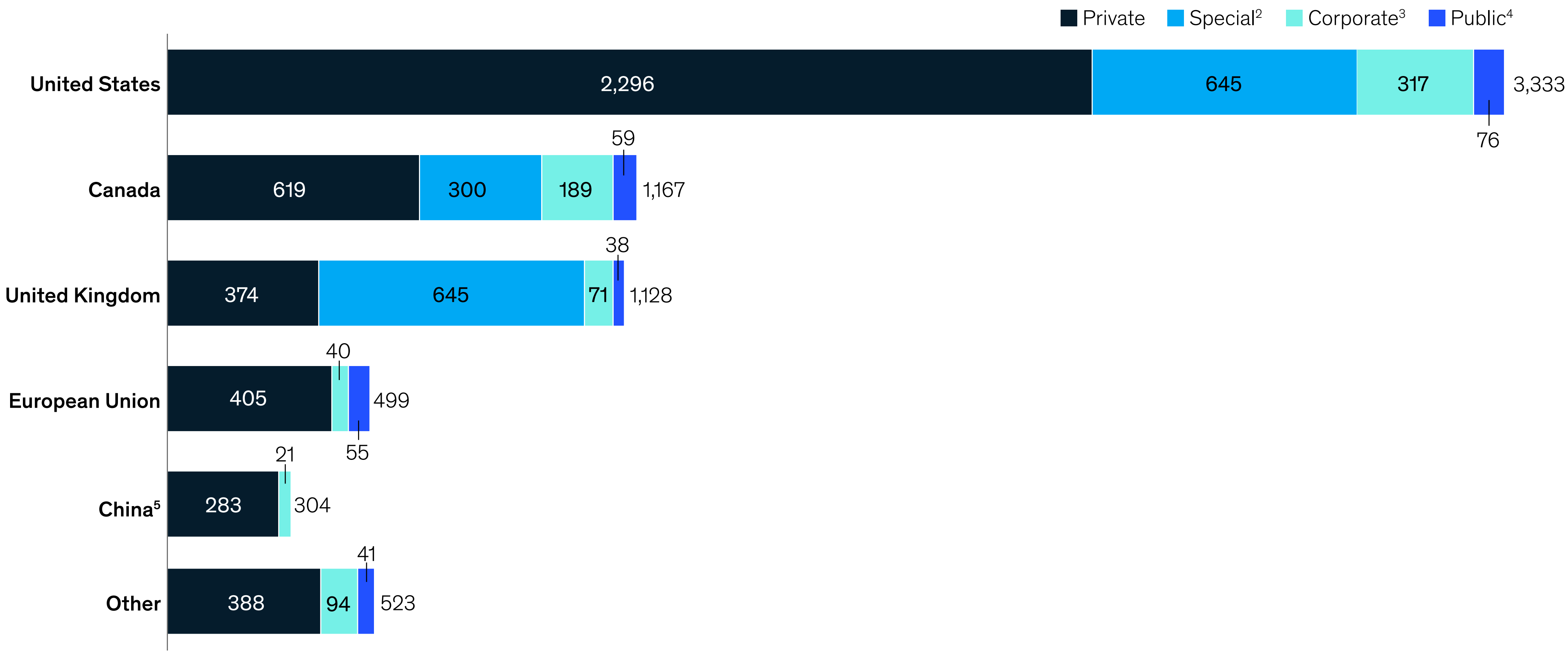
Company	**Country**	**Tech**	**Segment**	**Deal size,** $ million	**Deal year**
SandboxAQ	United States	Quantum sensing, Quantum communications, Quantum computing	Application software	500	2022
Rigetti Computing	United States	Quantum computing	Hardware manufacturing	345	2022
D-Wave Systems	Canada	Quantum computing	Hardware manufacturing	300	2022
Origin Quantum	China	Quantum computing	Hardware manufacturing	149	2022
ColdQuanta (now Infleqtion)	United States	Quantum computing	Hardware manufacturing	133	2022
IQM	Finland	Quantum computing	Hardware manufacturing	132	2022
Xanadu	Canada	Quantum computing	Hardware manufacturing	100	2022
Terra Quantum	Switzerland	Quantum sensing, Quantum communications, Quantum computing	Application software, QNO,[1] services	75	2022
Atom Computing	United States	Quantum computing	Hardware manufacturing	59	2022
Classiq	Israel	Quantum computing	Systems software	49	2022

[1] QNO = quantum network operator.

Source: Crunchbase; PitchBook

The majority of investments are in US companies, driven primarily by private investors.

Total investment in QT start-ups by location and primary investor type, 2001–22, $ million[1]

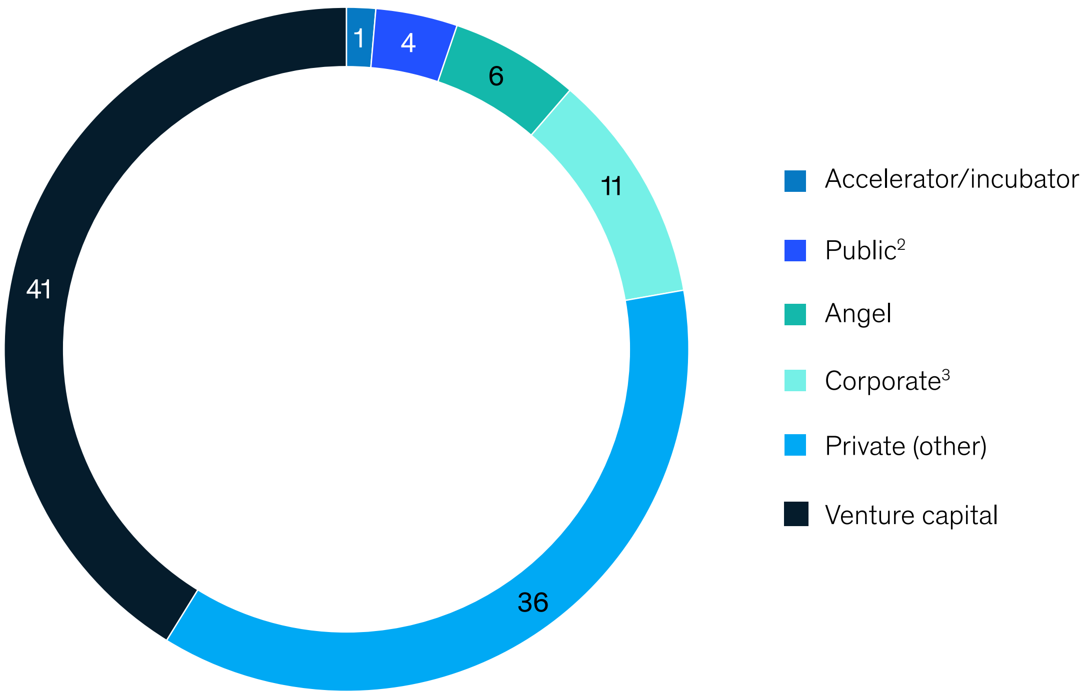


[1]Based on PitchBook data. Actual investment volume in QTs is likely higher. Figures may not sum to totals, because of rounding.
[2]Includes SPACs (eg, Rigetti Computing) and other special deal types (eg, Honeywell's investment of $300 million in Quantinuum).
[3]Includes investments from corporations 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.
[5]Data availability on start-up investment in China is limited. The overview includes all publicly available data on China. While actual investment is likely higher, we think that at this stage most investment awarded by China is to research institutions; other estimates place total private investments closer to $615 million.

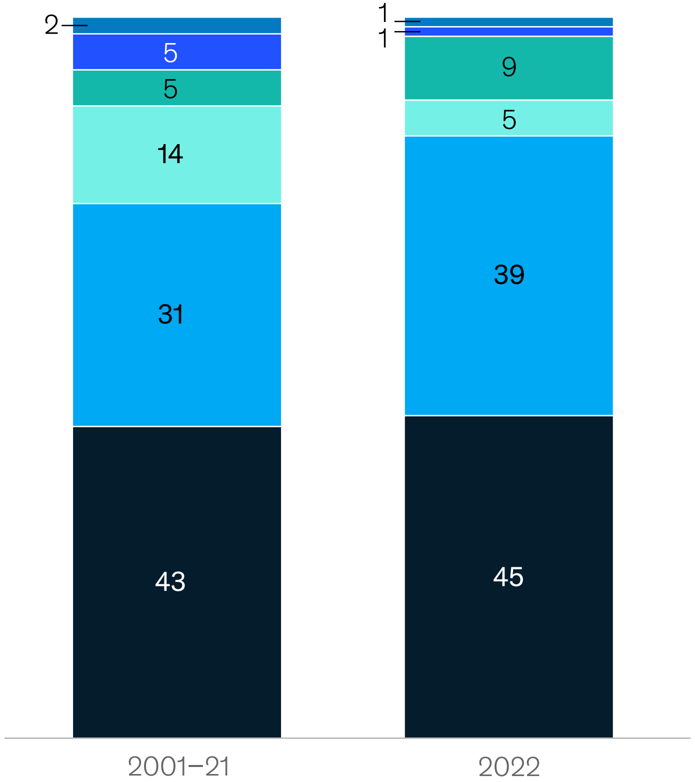
Source: ICV Thinktank; IT橘子(IT Orange); PitchBook

Venture capital and other private funding make up nearly 80 percent of QT inflows; venture capital, private, and angel investments grew in 2022.

Split of QT investments, by investor type, 2001–22, % of total investment value[1]



Change in QT investments, by investor type, 2001–21 vs 2022, % of total investment value

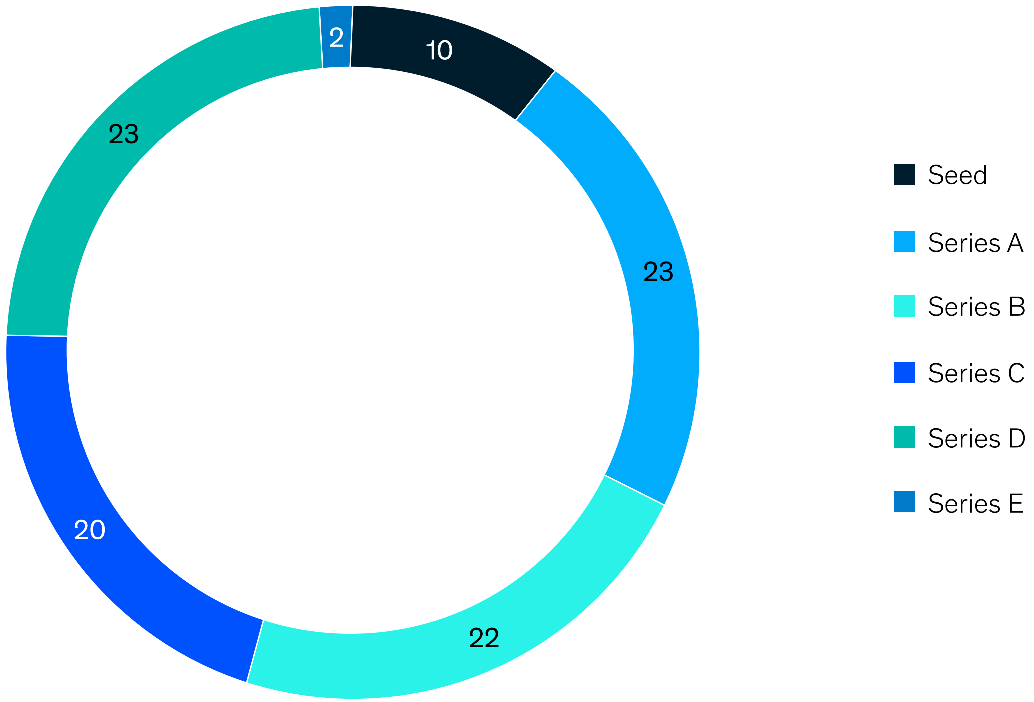


[1] Figures may not sum to 100%, because of rounding.
[2] Includes governments, sovereign wealth funds, and universities.
[3] Includes corporations, corporate venture capital, venture-capital-backed companies, and private-equity-backed companies investing in an external start-up; does not include corporations investing in internal QT programs.

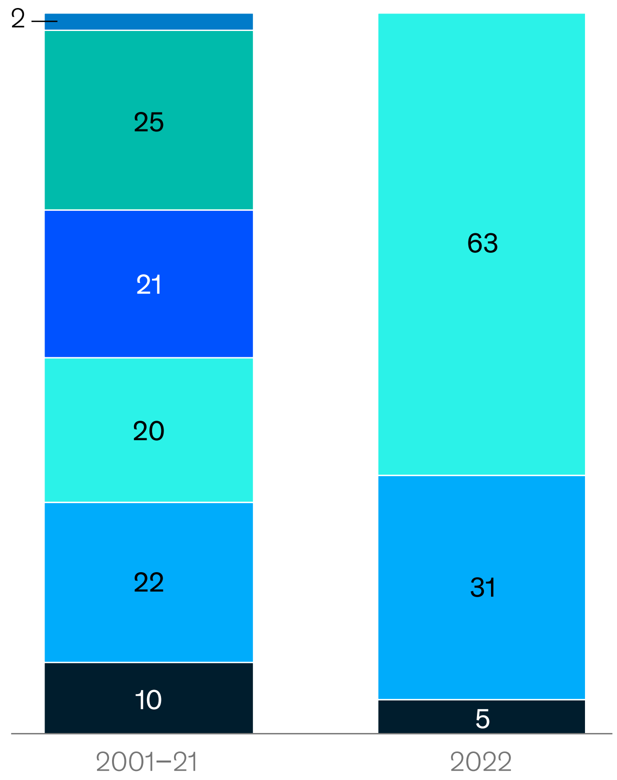
Source: PitchBook

Most investment went to early-stage start-ups in 2022.

Split of venture capital investments, by deal type, 2001–22, % of total investment value



Split of investments, by deal type, 2001–21 vs 2022, % of total investment value[1]

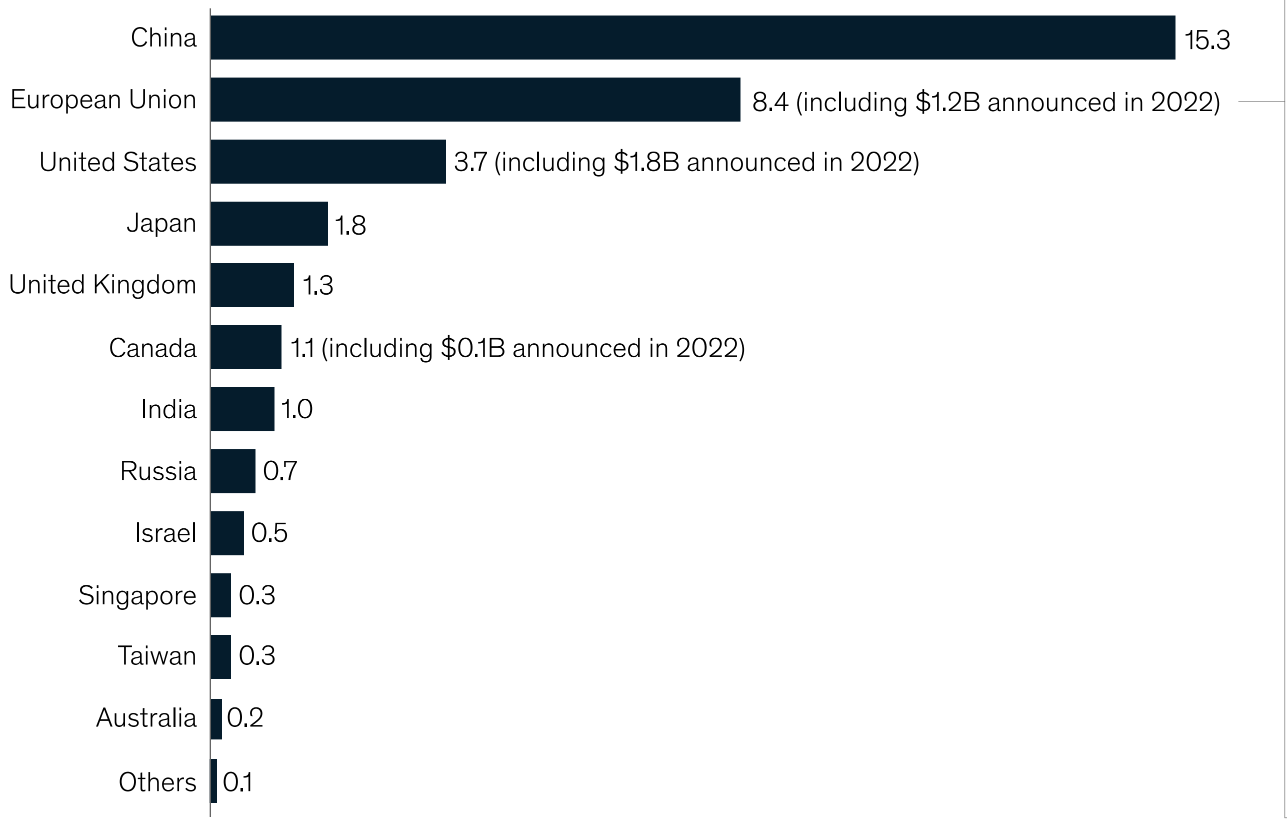


[1] Figures may not sum to 100%, because of rounding.

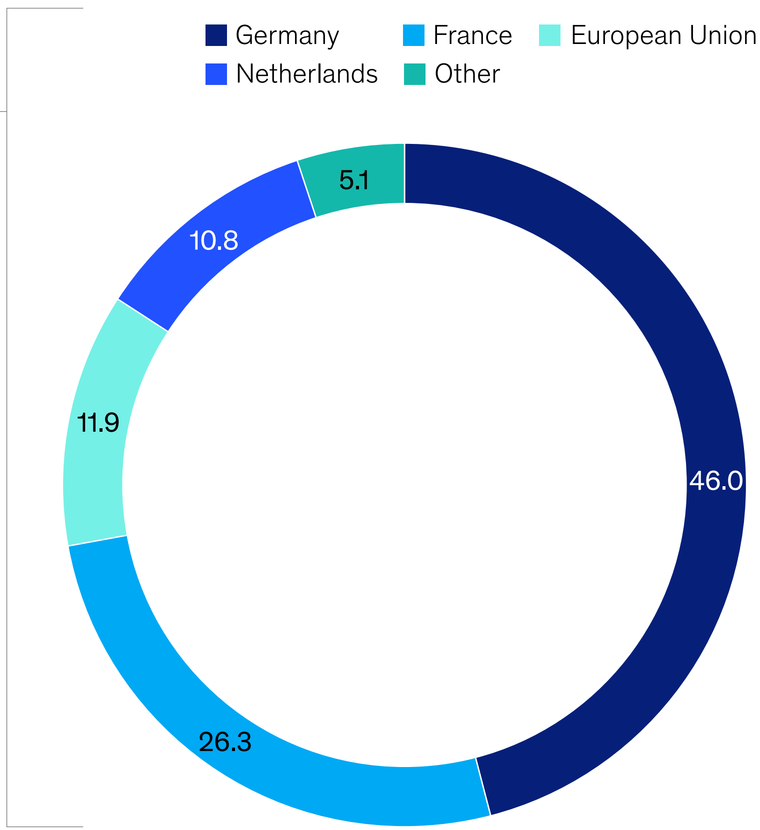
Source: PitchBook

The United States and European Union announced additional public funding for QT in 2022; however, China has announced the most public investment to date.

Announced governmental investment,[1] $ billion



EU public investment sources, %



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

Source: Johnny Kung and Muriam Fancy, *A quantum revolution: Report on global policies for quantum technology*, CIFAR, April 2021; press search

In China, government investment is helping drive quantum technology research and education.

~$15 billion
for QT as part of China's 14th five-year plan (2021–25)[1]

~52%
of all QT-related patents have been granted to Chinese researchers

33
companies active in QT

~$479 million
of private investments into Chinese QT start-ups

12
dedicated QT research institutions

News

- **2019:** China announced an education modernization plan that assumes 4 percent of GDP spend on education and differentiates quantum technology as one of four main areas of focus
- **2021:** Quantum information science was announced as a new major in the catalog of undergraduate majors in general colleges and universities
- **2021:** University of Science and Technology of China (USTC) was authorized to award doctorates in quantum science and technology, making it the country's first doctoral program in QT
- **2021:** In January, Chinese scientists set up an integrated quantum network that combines 700 fiber and two ground-to-satellite links and realized quantum key distribution between more than 150 users over a combined distance of 4,600 kilometers
- **2022:** A Chinese team announced it cracked 48-bit RSA using a 10-qubit quantum computer-based hybrid system, and could potentially do the same for 2048-bits
- **2023:** China has become the third country (besides the United States and Canada) with the ability to deliver a quantum computer for commercial use, which was developed by a Chinese enterprise

[1]Other sources put this figure at closer to ~$25 billion, but we based our estimate only on data produced with transparent methodology. China's five-year plans detail the country's economic development goals.

Source: IT橘子(ITOrange)

In Japan, private investment in QT remains low, though public investment is stimulating quantum efforts.

~$1.8 billion
of public investment

~14%
of all QT-related patents have been granted to Japanese researchers

17
companies active in QT

~$58 million
of private investment into Japanese QT start-ups

7
dedicated QT research institutions

News

- **2018:** Japan's Ministry of Education initiated MEXT Q-LEAP, a Quantum Leap Flagship Program with the goal of advancing QT across four areas: QC, QS, next-gen lasers, and quantum human resources
- **2019:** Japan started the Moonshot Project, with the goal of creating a fault-tolerant universal quantum computer by 2050
- **2021:** The Integrated Innovation Strategy Promotion Council, formulated by the Japanese government, proposed the creation of a Quantum Technology International Collaboration Hub at the Okinawa Institute of Science and Technology (OIST)
- **2022:** The government of Japan formulated the Vision of Quantum Future Society, with goals of ten million quantum users by 2030, subsidizing quantum technology start-ups, and establishing ecosystem-supporting public-private collaborations
- **2022:** Fujitsu and RIKEN Research Institute planned to jointly offer quantum computers to enterprise clients starting in April 2023

Source: IT橘子(ITOrange)

Quantum computing

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

Number of QC start-ups, by country, 2022

\+ change since 2021

		Start-ups	Incumbent companies	Public/government organizations	Academic groups
Top 7	United States	72 +12	9	18	67 +3
	Canada	28 +2	0	2	9
	United Kingdom	22 +3	1	2	14
	Japan	14 +1	1	0	7
	France	11 +3	1	3	9
	Germany	11 +4	2	1	7
	China[1]	9 +1	2	12	11
Rest of world		84 +10	1	19	55 +1
Total		**248** +36	**17**	**57**	**180** +4

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

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

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

Number of QC start-ups, by country, 2022

+ change since 2021

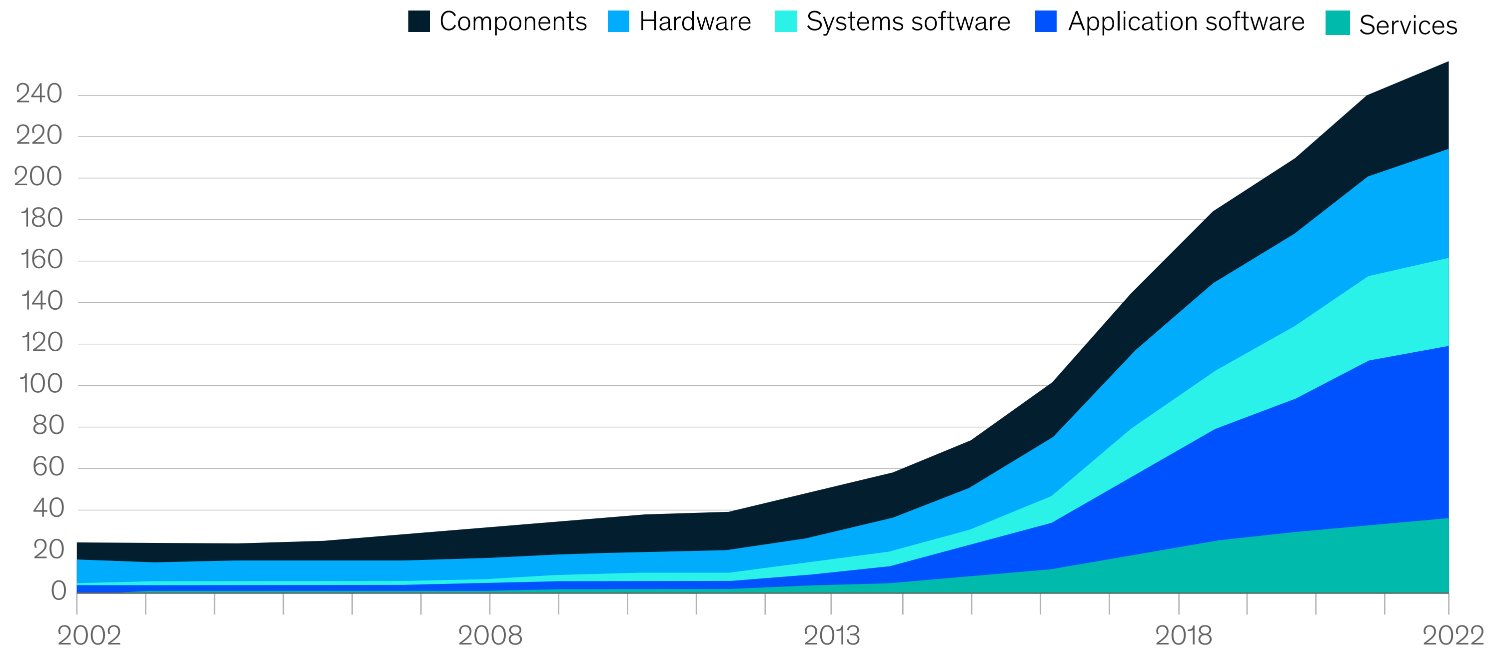
Country	2022	Change since 2021
United States	72	+12
Canada	28	+2
United Kingdom	22	+3
Japan	14	+1
Germany	12	+4
France	11	+3
China[1]	9	+1
Australia	8	+1
Spain	8	+1
Netherlands	7	+1
Finland	6	
India	6	+1
Israel	6	+2
Switzerland	5	
Sweden	3	+1
Denmark	3	+1
Colombia	2	
Poland	2	
Singapore	2	
Austria	2	
United Arab Emirates	2	
Italy	2	+1
Czech Republic	1	
Estonia	1	
Greece	1	
Hong Kong	1	
Bulgaria	1	
Liechtenstein	1	
Philippines	1	
Norway	1	
Portugal	1	
Romania	1	
Russia	1	
Taiwan	1	
Turkey	1	
Uruguay	1	
Ireland	1	
South Korea	1	+1
Total	**248**	**+36**

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

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

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

Number of QC start-ups founded (cumulative)



Number of QC companies founded in each year

2018	2019	2020	2021	2022
3	5	2	3	3
8	7	2	4	5
11	4	7	6	2
16	16	10	17	4
6	7	5	4	3
Total: 44	**39** (–11%)	**26** (–33%)	**34** (+31%)	**17** (–50%)

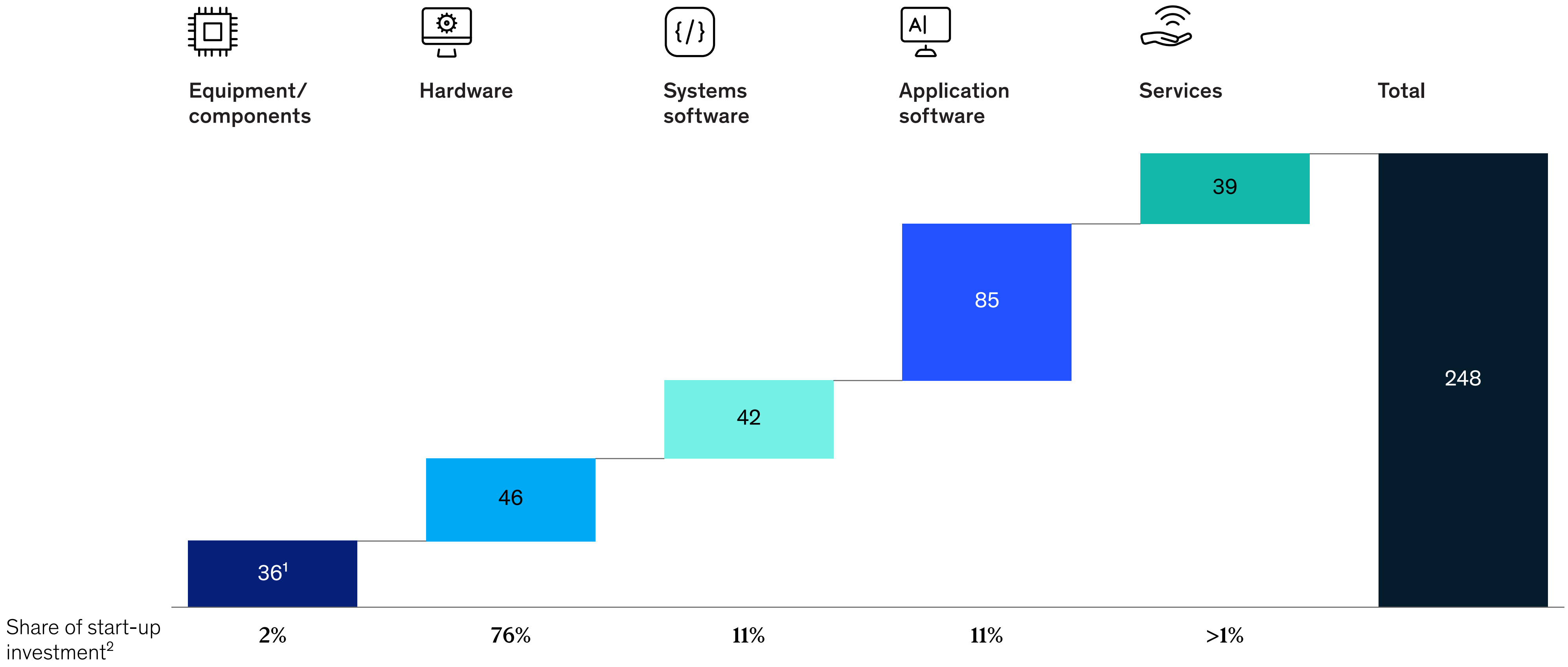
Potential hypotheses on the causes of the slowdown:

- **Lack of talent:** Most experienced specialists (generally academics whose research focus is QC) already work in a start-up.
- **Few working use cases:** Application start-up creation is hindered by limited working use cases and existing hardware patents.
- **Investor trends:** Investors prefer to invest in scale-ups and later-stage start-ups, limiting capital available for new companies.

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

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

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

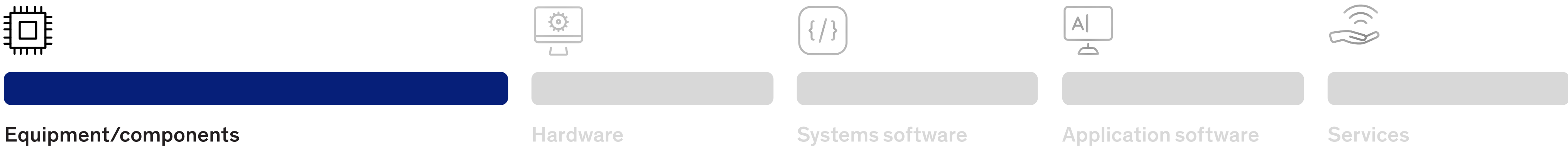


[1] There are more than 100 total suppliers; however, only 36 are start-ups specific to quantum computing.
[2] Based on public investments in start-ups recorded on PitchBook and announced in the press; includes announced deals for 2022; excludes investments in internal QT departments or projects by incumbents; actual investment is likely higher. Figures do not sum to 100%, because of rounding.

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

The QC equipment and components segment of the value chain is the most mature, with room for specialized players.

MATURE MARKET | **DEVELOPING MARKETS**



- The components segment is the only segment of the QC value chain that is generating significant revenue through sales to universities, research institutes, and technology companies.
- Players range from specialized QC players to general technology manufacturers (eg, electronics), scattered across a range of technologies.
- Product maturity varies per component, yet nearly all components still require customization by quantum players.
- Technology improvement is needed across component types to enable scaling to fault-tolerant QC. This leaves room for specialized players to enter the market.

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

QC hardware is dominated by big tech players and a few scale-ups.

MATURE MARKET

DEVELOPING MARKETS

Equipment/components

Hardware

Systems software

Application software

Services

There are currently five major hardware being developed: photonic networks, superconducting circuits, spin qubits, neutral atoms, and trapped ions.[1]

— Due to the complexity of the technology, the hardware segment has high risk and long development times. As a result, players require significant capital and highly specialized knowledge. The hardware segment today is dominated by technology giants, most of which entered the market a decade ago and focus on superconducting qubits.

— In the past three years, start-up companies in ion traps, neutral atoms, and photonic qubits have raised significant investment and are scaling up, eg, IonQ, PASQAL, PsiQuantum, etc.

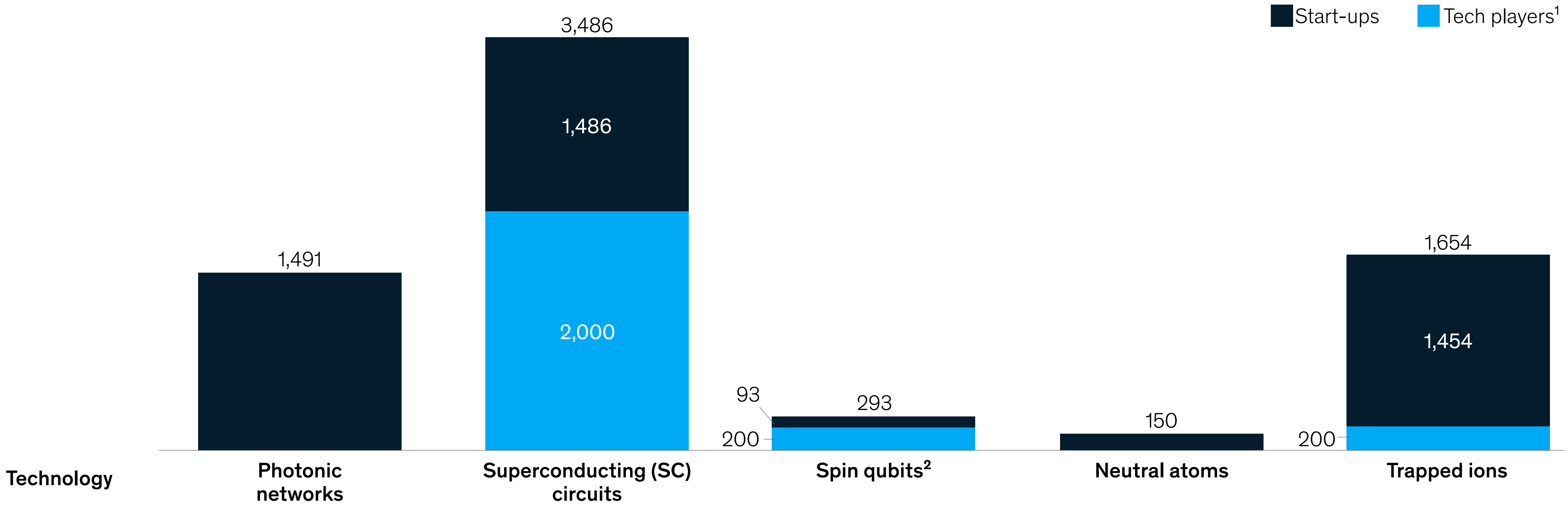
— Based on public announcements, superconducting qubits are the most developed, yet some experts believe photonic qubits are technologically ahead.

[1] Additional technologies in the exploratory phase are likely to join these five, including, for example, Majorana fermions.

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

In hardware, tech incumbents invest most in superconducting circuits, while start-ups invest more in ions and photonic networks.

Investment, $ million



[1]Assumptions: $500 million per major player (Google, IBM, Alibaba, AWS), $200 million per medium player (Honeywell before merger with CQC into Quantinuum, Intel).
[2]We examine electron spins in silicon quantum dots, as other spin qubits are generally not considered for applications in quantum computing, eg, NV centers in diamond are unlikely to be a good qubit for computing; however, they can serve as quantum sensors.

Source: Crunchbase; Capital IQ; Pitchbook; Quantum Computing report; expert interviews

The systems software market is split between full-stack and dedicated software players; most products are in the prototype phase.

MATURE MARKET

DEVELOPING MARKETS

Equipment/components

Hardware

Systems software

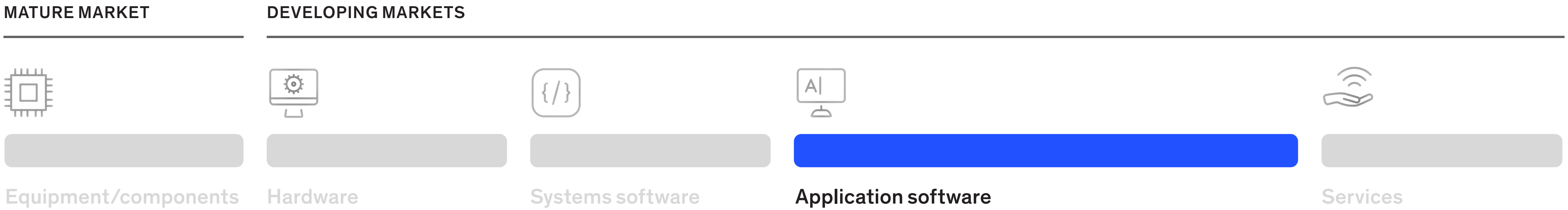
Application software

Services

- Systems software players offer logical programming languages for quantum computers as well as compilers and error-correction software. Some systems software players offer dedicated control software for quantum hardware.
- The systems software market is divided between leading full-stack players, who offer programming languages for their own hardware, and dedicated software players offering hardware-agnostic solutions.
- Leading systems software solutions are available in prototype form, mostly open source. Existing solutions are suitable for the small-scale quantum hardware available today and require further development to support large-scale, fault-tolerant quantum computers.

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

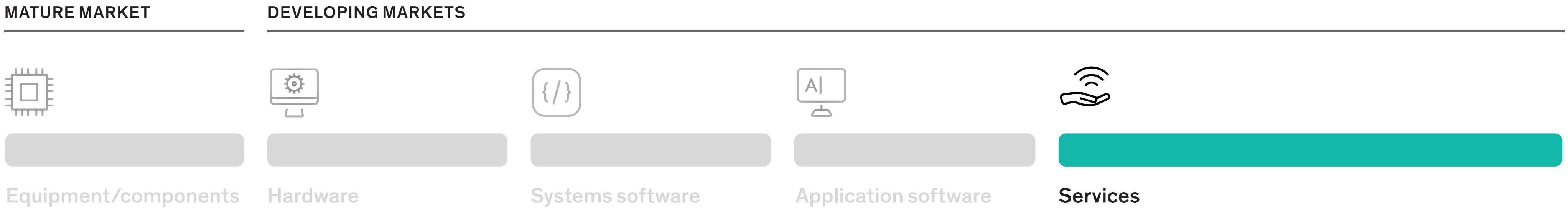
The application software segment is not yet fully mature and is far from saturated.



- The application software market has emerged in the past few years. Key players are hardware and systems software players offering full-stack solutions. They operate across all industries, or focus on finance, pharmaceuticals, and chemicals. Off-the-shelf products do not yet exist; most business models are still based on exploratory research projects in collaboration with industry.
- The development of end-to-end quantum solutions for business problems still takes years; due to the wide range of potential quantum applications in various industries, the application software market is far from saturated.
- Some players in this segment have chosen to focus on developing quantum-inspired algorithms—algorithms that are run on classical hardware but incorporate principles and ideas from quantum computing. These algorithms have shown great promise and could be an avenue to realize value without a fault-tolerant computer.

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

The services segment is split between consulting, education, and cloud services.



- The cloud services market is in an early stage of development. Players offer public access and premium computing time on existing hardware for education and experimentation. Cloud players are split between upward integrating hardware players and dedicated cloud players offering access to third-party hardware. Significant growth of this segment is expected once quantum hardware matures.
- Consulting services and joint research projects are a key source of income for hardware and software players. In addition, there are few dedicated consulting players as well as players offering QC education and media.

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

Quantum computing

Industry adoption

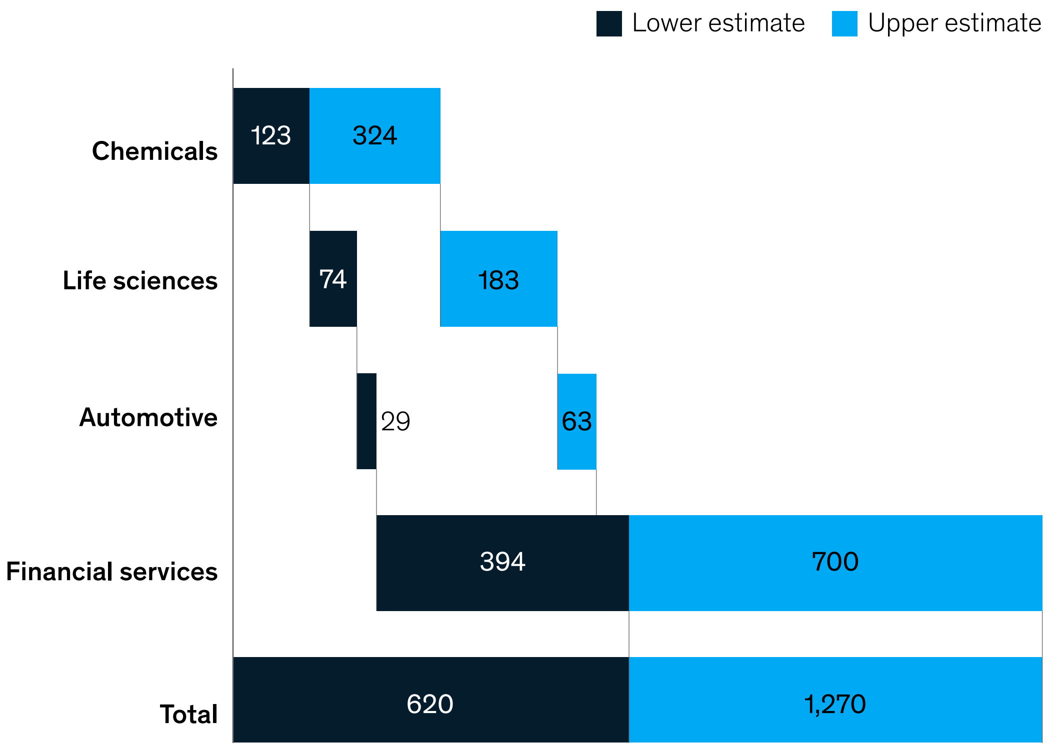
The estimated value at stake for QC in the four industries most likely to see impact first has now reached nearly $1.3 trillion.

Economic value + Incremental ++ Significant +++ Disruptive

Industry	Key segment for QC	2025–30	2030–35
Global energy and materials	Oil and gas	+	++
	Sustainable energy	+	+++
	Chemicals	++	+++
Life sciences	Pharmaceuticals	++	+++
Advanced industries	Automotive	++	++
	Aerospace and defense	+	++
	Advanced electronics	+	++
	Semiconductors	+	++
Finance	Financial services	++	+++
Telecom, media, and technology	Telecom	+	++
	Media	+	+
Travel, transport, and logistics	Logistics	+	++

Four industries expected to see first impact

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



Source: “Quantum computing use cases are getting real—what you need to know,” McKinsey, December 14, 2021; expert interviews

The use cases most likely to have the highest value over the long term are in the finance and life sciences sectors.

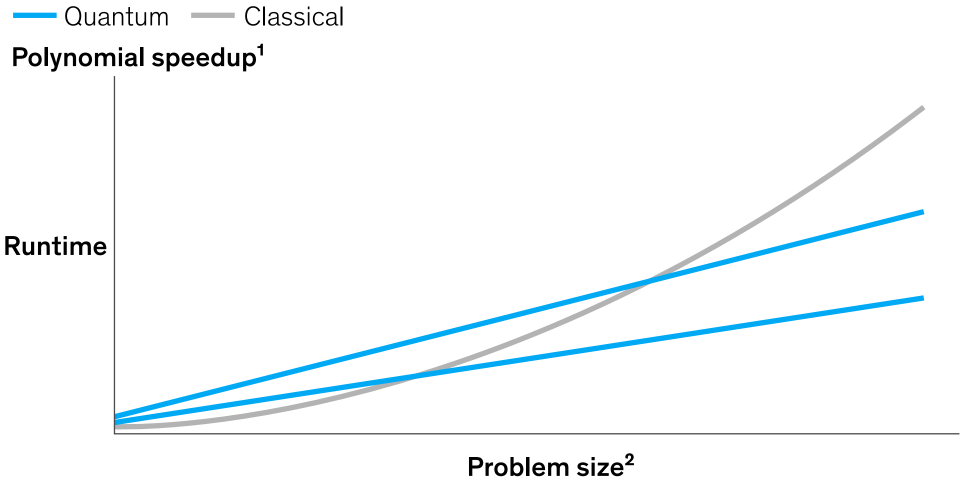
Incremental impact | Significant impact | Disruptive impact

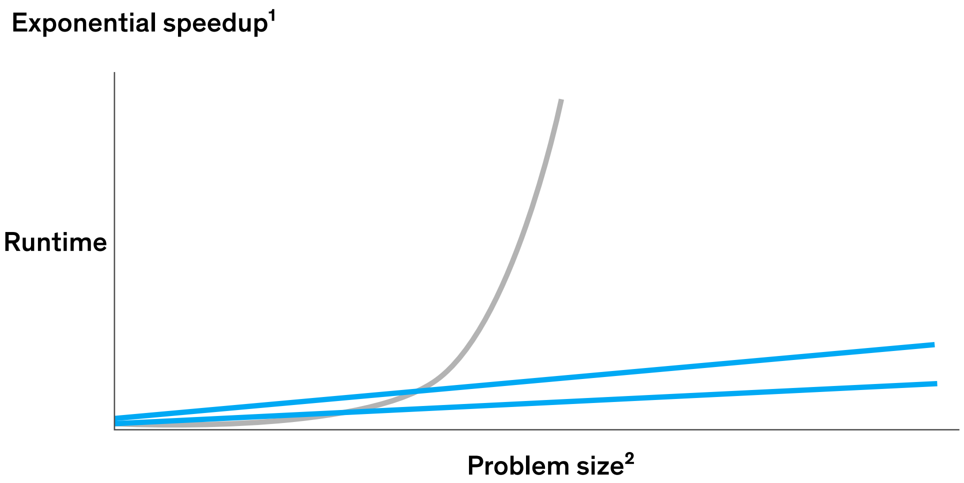
Problem archetype	Finance	Life sciences	Aerospace and defense	Chemicals	TTL[1]	Automotive and assembly	EPNG[2]
Factorization eg, breaking RSA encryption	Disruptive	Incremental	Disruptive	Incremental	Significant	Incremental	Incremental
Quantum simulation eg, calculating a molecule's spectrum	Incremental	Disruptive	Significant	Disruptive	Significant	Significant	Significant
Optimization eg, finding the best schedule for planes	Disruptive	Disruptive	Significant	Incremental	Disruptive	Significant	Significant
Quantum ML and AI eg, processing natural language	Disruptive	Significant	Incremental	Significant	Significant	Significant	Significant
Sampling and search eg, finding a match in an unstructured database	Disruptive	Incremental	Incremental	Incremental	Significant	Significant	Incremental

[1] Travel, transport, and logistics.
[2] Electric power and natural gas.

Source: Expert interviews

Economic value is unlocked through speedup, which depends on algorithm complexity, execution time, and problem size.





Algorithm complexity

The different natures of classical and quantum algorithms lead to inherent computation advantages in different problems. For certain problems, quantum algorithms can be polynomially or exponentially less complex than the classical algorithm.

Execution time

The total computation time is highly dependent on the different hardware (eg, gate speed, readout cleaning) and architecture (eg, data loading) used in high-performance computing (HPC) and QC; therefore it is different from algorithm complexity.

Problem size

The practicality of the quantum algorithm is also dependent on the problem size. If a problem is too small, then the speedup is not significant enough to be adopted; if a problem is too big, even with the speedup, it can still be too big to solve practically.

[1] Two quantum algorithms are considered with slightly different speedups for illustrative purposes. "Speedup" is how much faster quantum computing solves a problem as compared to classical computing.
[2] Problem in consideration is generic and imaginary for illustrative purposes.

Source: Expert interviews

Before a fault-tolerant quantum computer is available, QC will likely provide speedup for three of the four types of problems for which it has demonstrated advantage.

Simulation problems

Compared to classical computations, QC is expected to enable precise simulation molecules (eg, electronic structure or molecular dynamics).

Optimization problems

Optimization algorithms aim to minimize the cost function based on multiple parameters. Classical algorithms are advantageous in sectioning the bigger problems into digestible smaller problems which quantum algorithms can calculate faster.

Hybrid ML/AI problems

Quantum algorithms can reduce the training time for ML/AI models, especially in the most computationally intensive layers by providing at least polynomial speed up in learning certain data classes.

Cryptography problems

Quantum algorithms can pose danger to services including online/mobile communication and bank transfer by breaking current classical encryption protocols. Quantum technology can provide new encryption protocols with enhanced security.

In the near term, leveraging a hybrid operating system to distribute a complex problem between HPC and QC can bring a bigger computational advantage than either system alone

Source: Partnership for Advanced Computing in Europe, National Renewable Energy Laboratory

Hybrid or heuristic alternations offer options for exploring the full potential of NISQ and early fault-tolerant devices.

We cannot fully capture value today...

Fault-tolerant (FT) algorithms cannot be performed on noisy intermediate-scale quantum (NISQ) or early FT devices at scale to demonstrate quantum advantages, due to hardware limits, such as circuit volume, execution time, and noise level

...but hybrid or heuristic algorithms could harness some value

	Description	Pros	Cons
Heuristics algorithms	Use digital simulation such as variational quantum algorithms (VQA) or analogue simulation including annealing to replace FT subroutine such as quantum phase estimation (QPE) on NISQ devices	Protect the quantum-ness of the algorithm to potentially realize advantage Explore and leverage the structure of different hardware technologies to prepare for FT	Speedup of heuristic algorithms is not clear and problem dependent Dependent on NISQ development Digital simulation relies heavily on two-qubit gate, which is limited by coherence time on NISQ devices
Hybrid algorithms	Using classical computers to simulate quantum processes based on the system (Hamiltonian) to replace FT routine such as QPE on NISQ devices, such as maximum-likelihood quantum amplitude estimation (MLQAE)	Clarity on speedup compared with heuristic algorithms Less dependent on quantum hardware	Less clear/lack of general classical approach to replace FT algorithms; early stage and problem dependent

Source: Jean-Charles Cabelguen,"Why analog neutral atoms quantum computing is the most promising direction for early quantum advantage," Pasqal, July 6, 2022; Adam Callison and Dan E. Browne, "Improved maximum-likelihood quantum amplitude estimation," arXiv, September 7, 2022

NISQ-era experimentation helps advance development of FTQC hardware; algorithmic learning is less transferable.

	Noisy intermediate-scale quantum (NISQ)	Fault-tolerant quantum computation (FTQC)
Description	NISQ refers to roughly 50 to a few hundred qubit quantum computers able to perform tasks surpassing classical computers but noise in the quantum gates limits the size of the circuits on which algorithms can be executed with reliability. Industrial advantage expected at 200–1,000 qubits.	FTQC refers to universal general-purpose quantum computers with physical error rates below a certain threshold, so algorithms run accurately and execute scale efficiently in the presence of faults during the computation.
Characteristics of algorithms	• Lack of performance guarantees, slower • Robust to error • Short circuit depth • Often use heuristic and classical computation required as aid	• Low error tolerance • Higher accuracy • Extensive quantum volume required • Short execution time required
Algorithms	VQE, QAOA, variational QML	Shor's, Grover's, quantum counting, QITE, QPE

The future is FTQC: the development of fault-tolerant hardware is aided by certain NISQ-era innovations; algorithmic learning carries over less easily due to fundamental differences in applicable algorithms and compilers between the two forms of QC.

Quantum communications

QComms start-ups continue to be created, though at a rate slower than QC start-ups.

Number of QComms start-ups by country

+ change since 2021

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

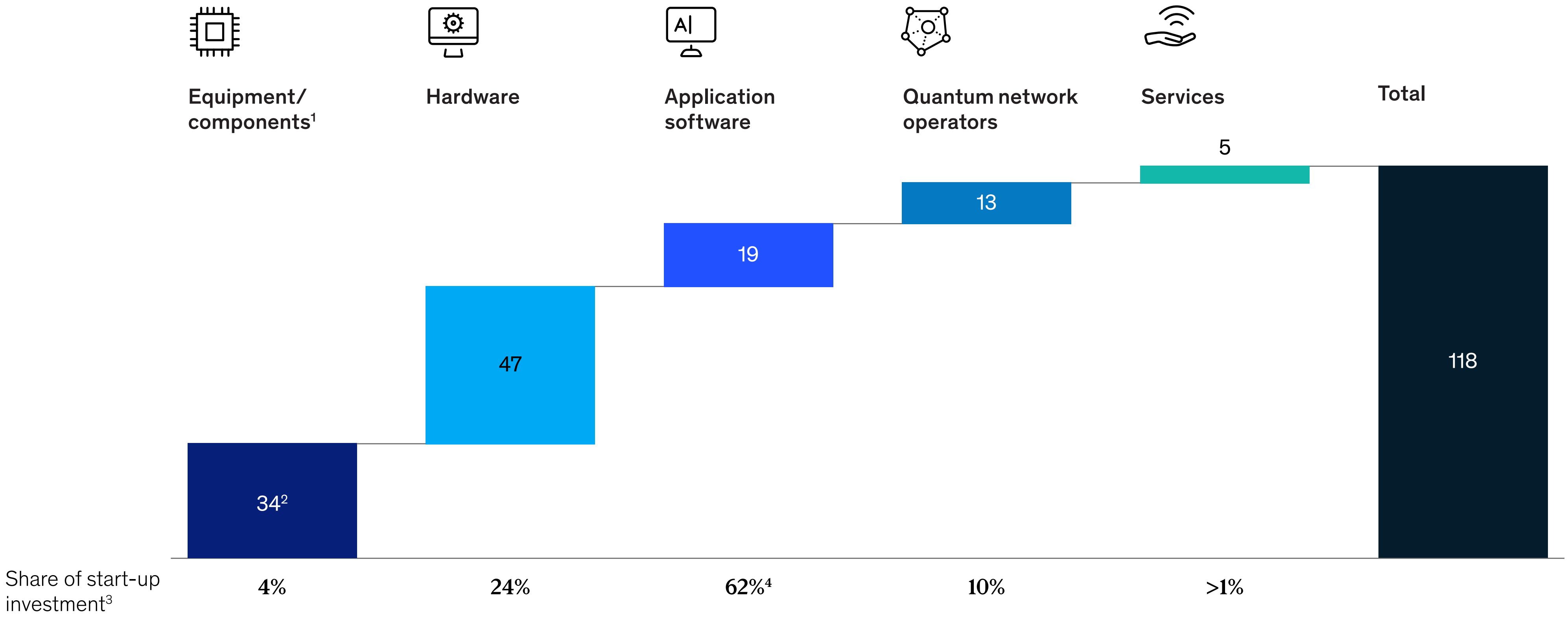
Country	2022	
Australia	2	
India	2	
Russia	2	+1
Colombia	1	
Finland	1	
Israel	1	
Bulgaria	1	
South Korea	1	
Scotland	1	
Liechtenstein	1	+1
Total	**95**	**+5**

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

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

QComms application software start-ups garner the most investment but make up only 16 percent of players.

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



[1]Includes start-ups and incumbents that develop or offer QT products; see methodology pages for details.
[2]There are more than 100 total suppliers; however, only 34 are start-ups specific to quantum communications.
[3]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. Figures do not sum to 100%, because of rounding.
[4]Application software investment is driven by large deal ($400 million) for Arqit (United Kingdom) to develop quantum satellite communication.

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

Equipment and components are the mature aspects of the QComms value chain.

Overview of QComms players

MATURE MARKET	DEVELOPING MARKETS			
Equipment/components	**Hardware**	**Systems software**	**Application software**	**Services**
The equipment/components segment is split between general component suppliers and specialized QComms players.	Big global players have entered the hardware segment of the QComms market, yet medium-sized start-ups are technologically more advanced. Partnerships are formed to bridge the gap.	The application software market is relatively immature. Various start-ups are scaling up.	Various telecommunications providers have started to invest in quantum communications; these are likely to fulfill the role of quantum network operators in the future.	Few consulting services players of low maturity have entered the market; their focus is primarily on security, or QT in general.

The **core parts** of the quantum communications ecosystem **(hardware and software)** do not have commercial products yet. Revenue is generated mainly through component players, consulting services, and joint research projects.

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

Quantum sensing

Two new players have emerged in the QS ecosystem.

Number of QS start-ups by country

+ change since 2021

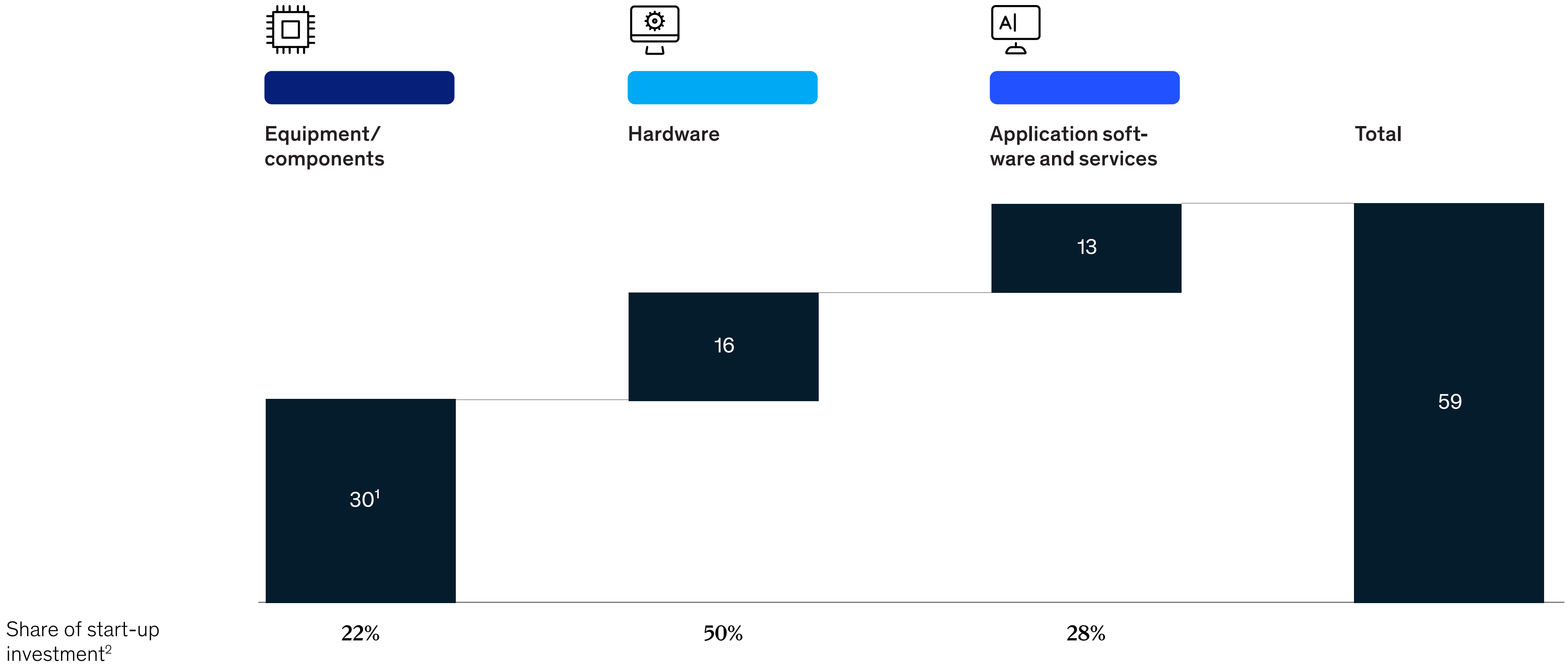
Country	2022	+ change since 2021
United States	14	+1
Switzerland	5	
Germany	5	+1
France	4	
United Kingdom	4	
China[1]	3	
Netherlands	2	
Denmark	2	
Australia	1	
Canada	1	
Finland	1	
Japan	1	
Singapore	1	
Sweden	1	
Turkey	1	
Total	**46**	+2

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

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

In QS, half of the players are in components; however, more investment has flowed to hardware manufacturers.

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; expert interviews

Equipment and components are the most mature aspect of the QS value chain.

MATURE MARKET

Equipment/components

The components segment of the QS market is most mature; manufacturers sell commercial products, but push-button solutions do not yet exist.

DEVELOPING MARKETS

Hardware

Hardware products are mostly at the level of prototypes. They require optimization in price, size, and weight to become competitive beyond niche markets. Large incumbents are partnering with smaller players to drive industrialization in QS.

Application software and services

The application software and services segment has few players; it is expected to grow as hardware matures.

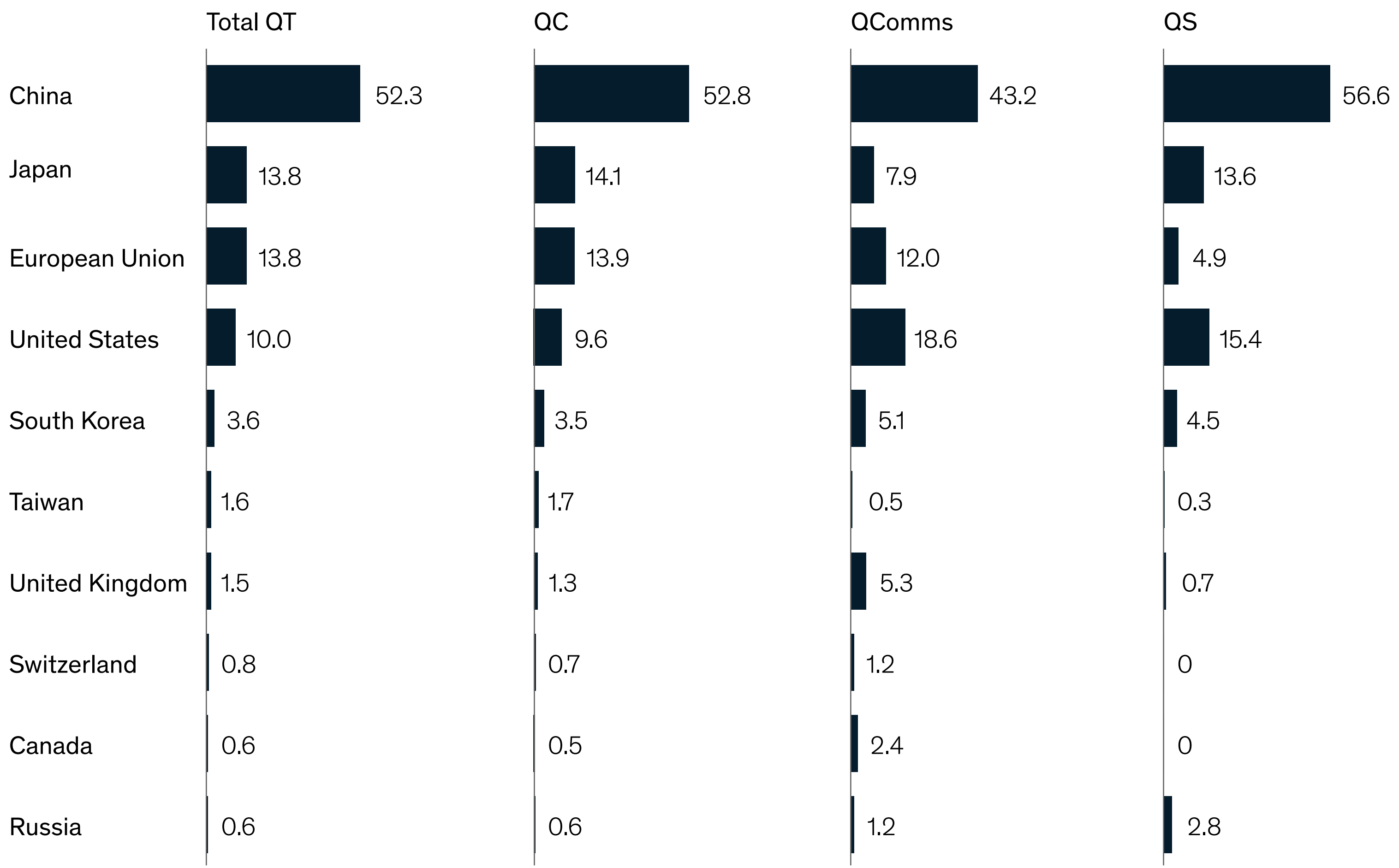
The **core parts** of the quantum sensing ecosystem **(hardware and software)** do not have commercial products yet. Revenue is generated mainly through component players, consulting services, and joint research projects.

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

Global technology progress

Over half of QT patents have been granted to Chinese companies.

Share of quantum patents by company's HQ country, 2000–22,[1] %



Takeaways:

— China has increased its share of patents in recent years, across all technologies; Chinese government policies are a strong factor.

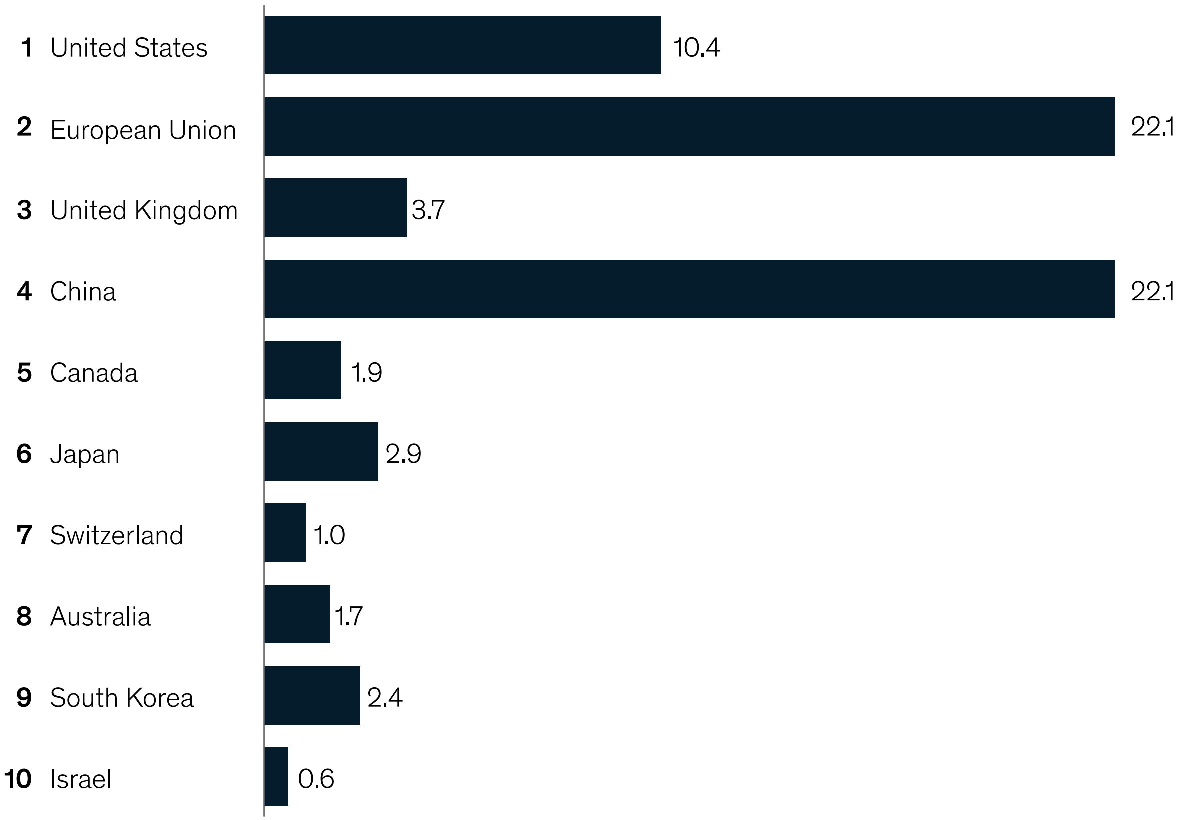
— Japan has been among the top 3 in QT patent development since the early 2000s, indicating a high degree of QT industry adoption and government influence.

[1]Only 50% of headquarters for patent applications are disclosed. Figures may not sum to 100%, because of rounding.

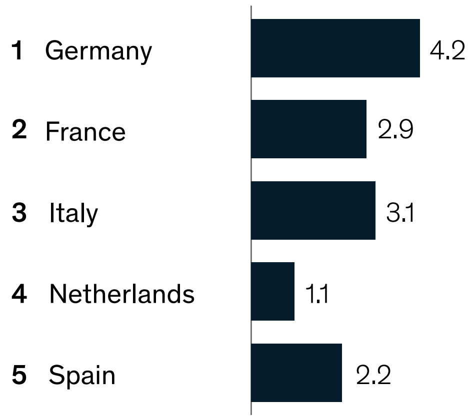
Source: Innography; expert interviews

While the European Union and China publish the most on QT, US publications are considered the most impactful, as measured by the h-index.

Top 10 countries worldwide 2021, sorted by h-index rank
Share of articles and country's h-index in quantum-relevant publications,[1] 2021, %



Top 5 EU countries, sorted by h-index rank
Share of articles and h-index, 2021, %



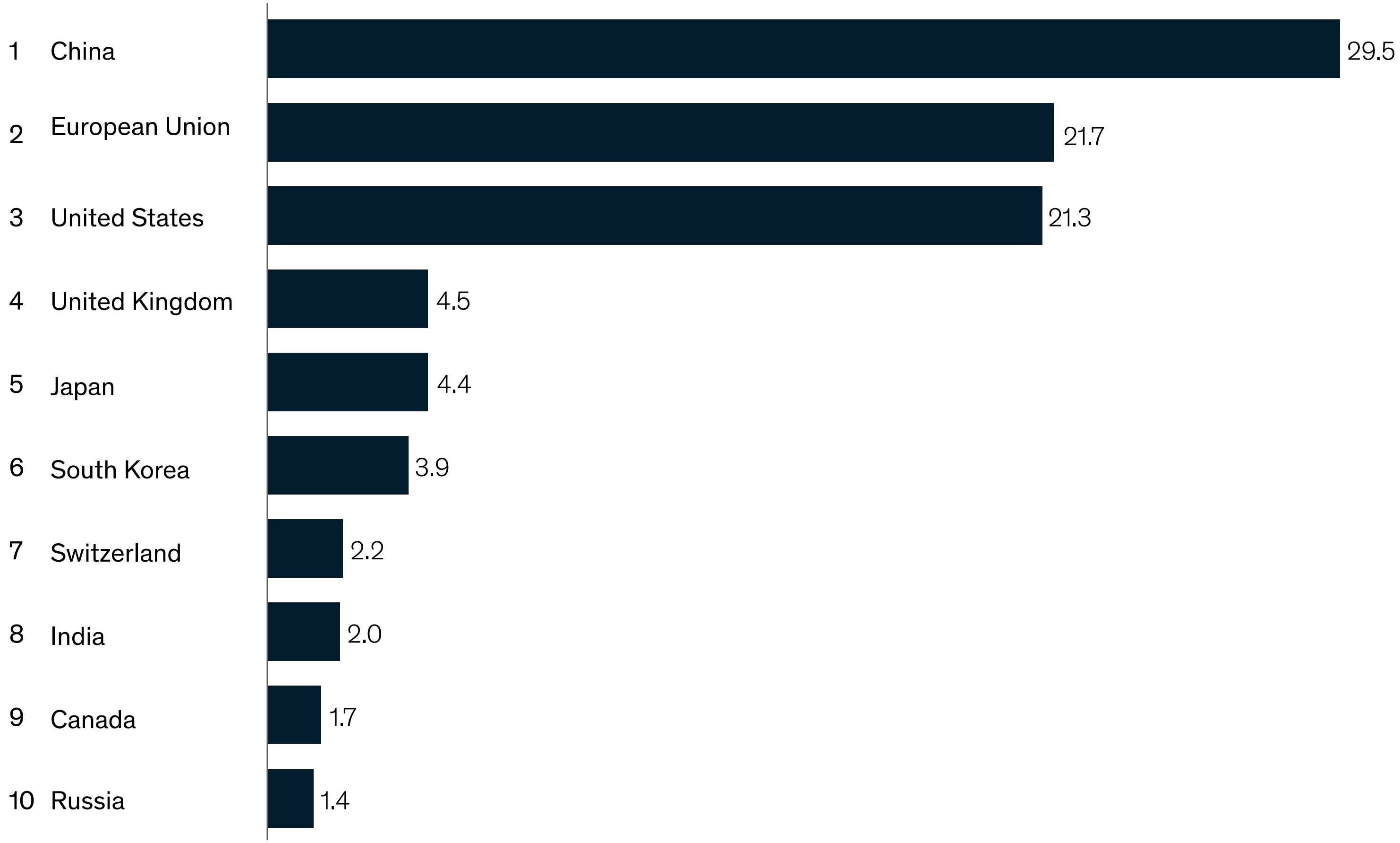
[1] The h-index is the number of articles (h) in a country that have been cited at least h times; quantum-relevant publications = publications in computer science, mathematics, and physics.

Source: SCImago Journal & Country Rank

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

Top 10 countries worldwide 2022, by share in scientific publications

Share of authors from country's research institutions contributing to quantum-relevant publications,[1] %

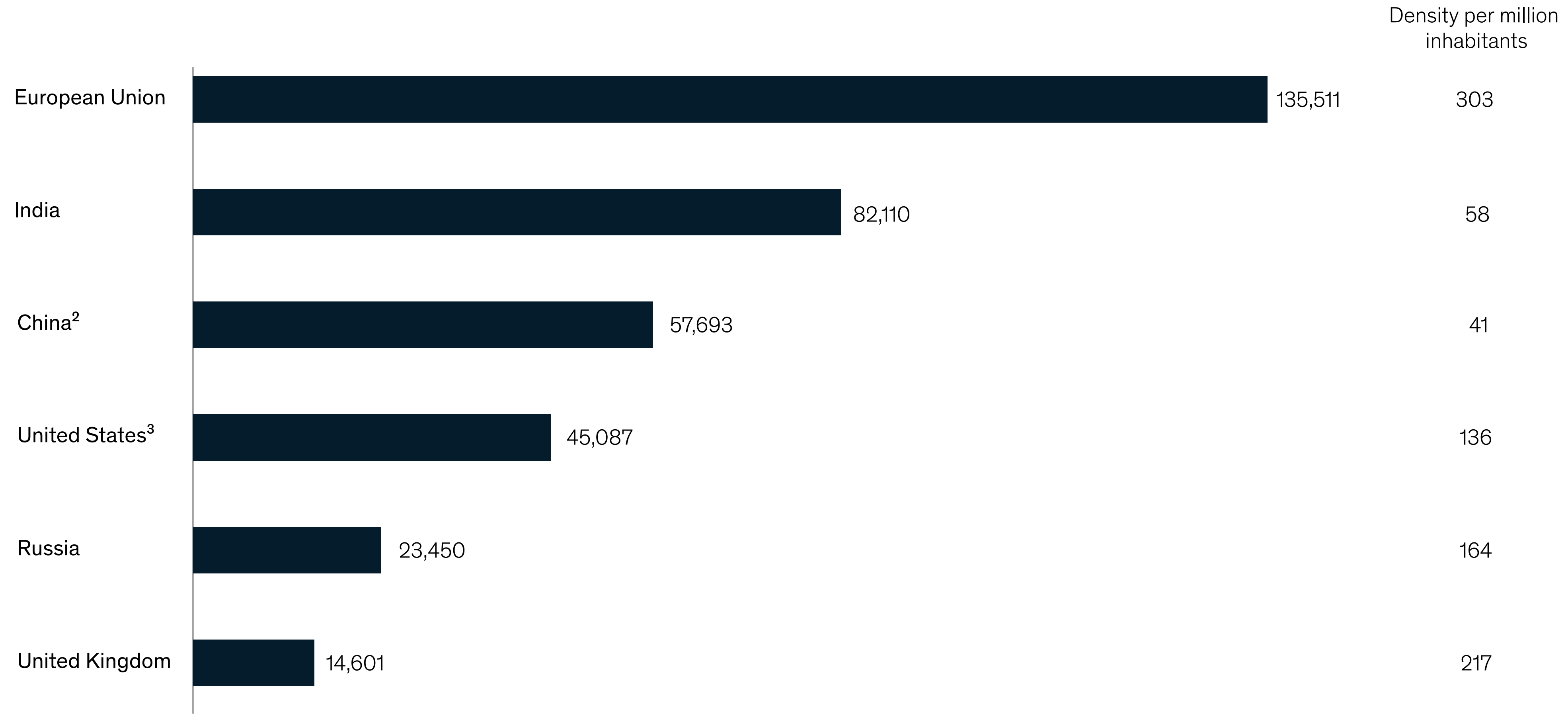


[1] Includes publications from October 1, 2021, to September 30, 2022. Quantum-relevant publications defined as publications in physical sciences.

Source: Nature Index

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

Absolute number of graduates in QT-relevant fields,[1] 2020

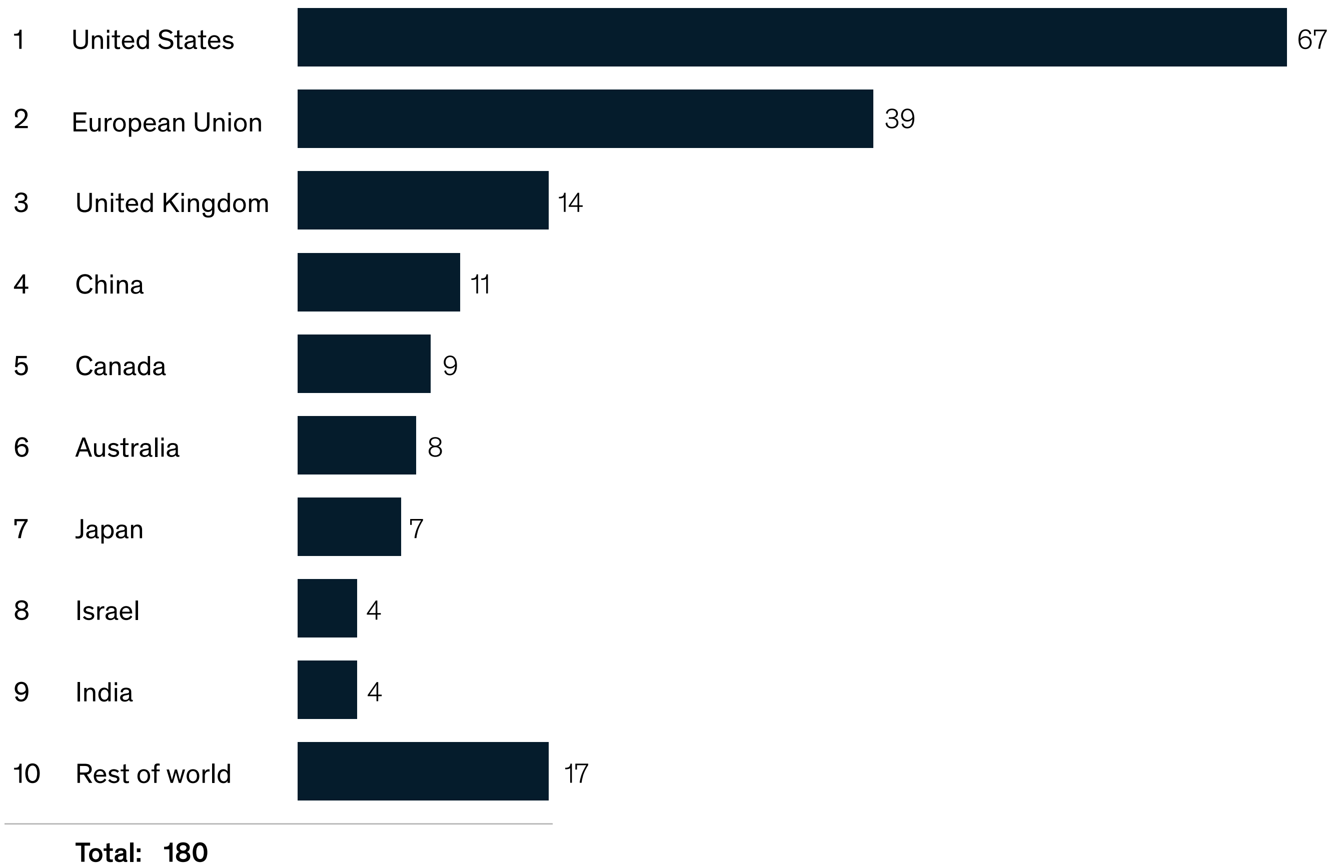


[1] Graduates of master's level or equivalent in 2019 in biochemistry, chemistry, electronics and chemical engineering, information and communications technology, mathematics and statistics, and physics.
[2] High-level estimates.
[3] The actual talent pool for the United States may be larger, as bachelor's programs are longer and master's programs are less common.

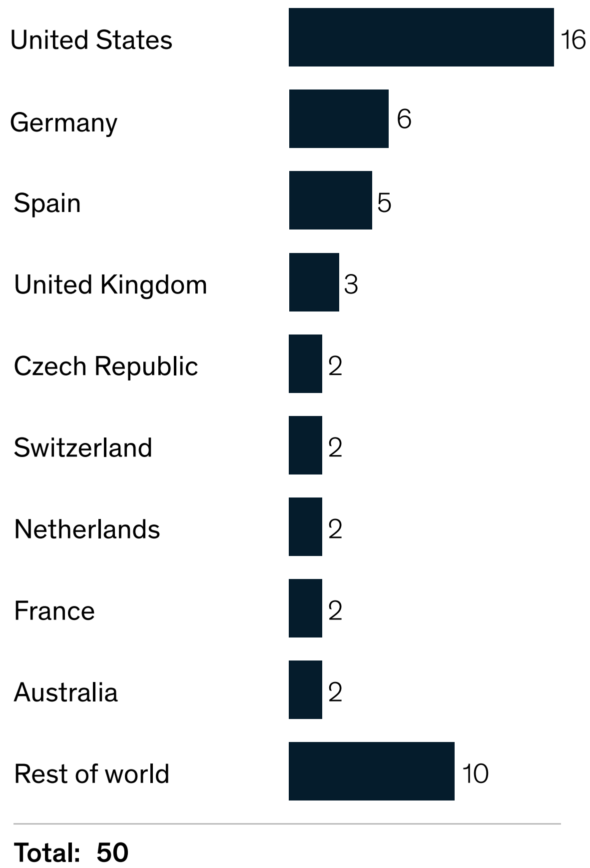
Source: National government websites; OECD

The number of universities offering QT master's degrees has increased to 50, a 74 percent increase since 2021.

Top countries for universities with QT research programs, 2022, number of universities per country

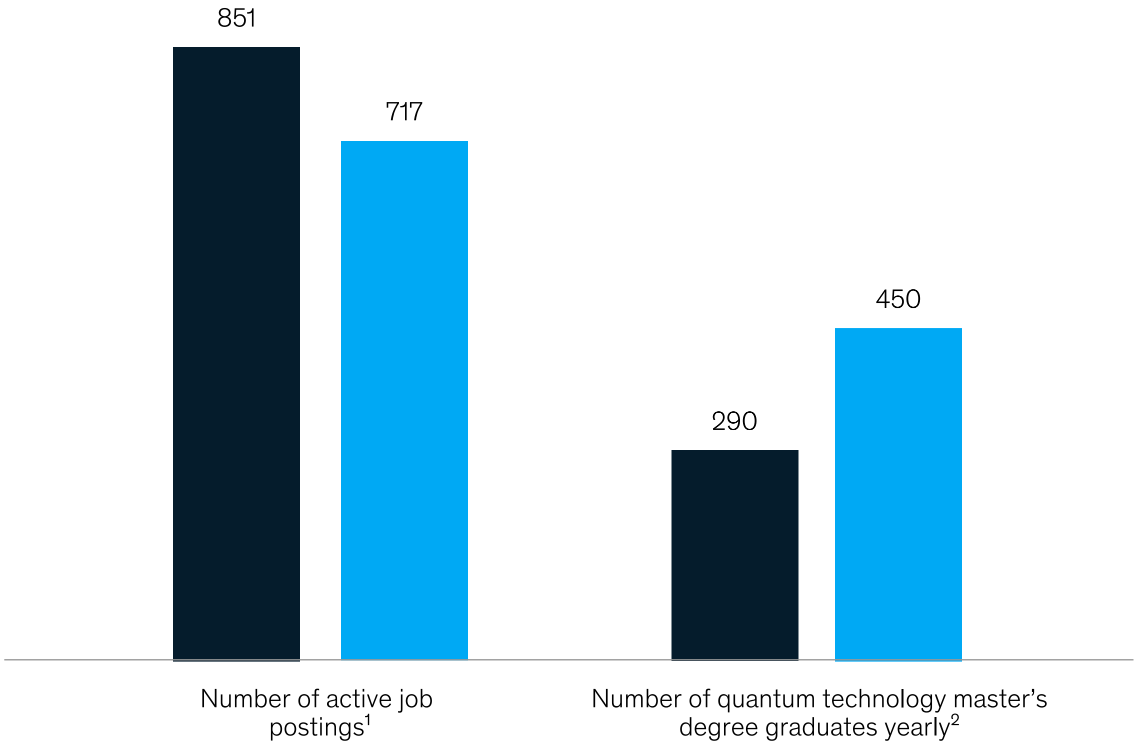


Universities offering QT master's degrees, 2022, number of universities per country



Source: QURECA; press search

While the QT talent gap has narrowed, there is still a shortage; upskilling graduates in QT-relevant jobs can help.



~350,000

graduates per year in quantum technology–relevant fields[3]

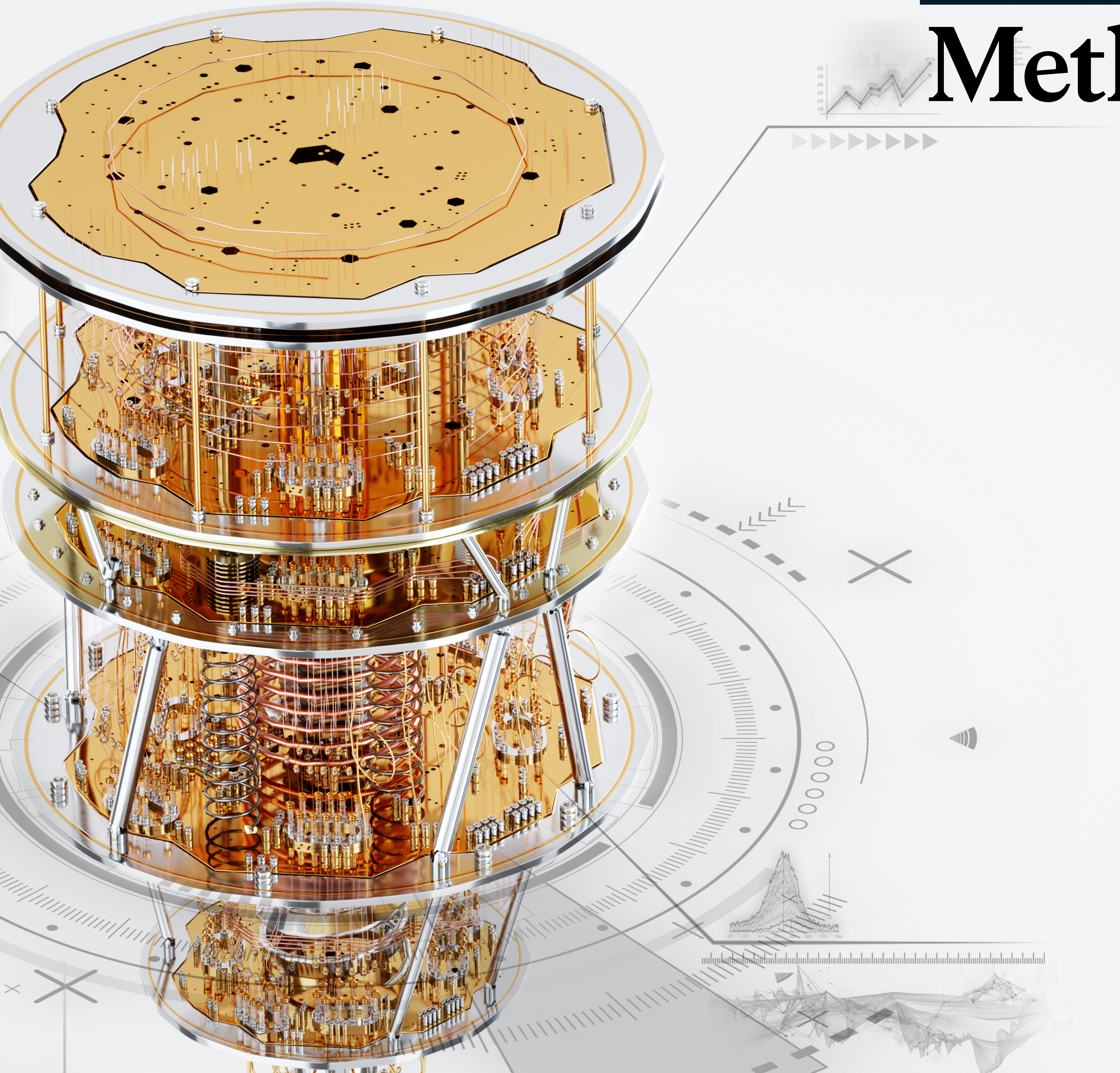
Takeaways:

- The number of job postings outstrips qualified talent by as much as three to one.
- Job openings increased nearly 19% year over year and the number of master's-level graduates increased by 55%.
- As a result, the talent gap narrowed in 2022.
- However, there are still fewer QT-skilled job-ready graduates than positions open for them.
- Upskilling programs could potentially help narrow the talent gap, given the numbers of graduates with QT-relevant knowledge in adjacent fields.

[1] For 2021, number of active job postings as of December 2021, and for 2022, monthly average number of active job postings.
[2] Estimate based on the number of universities with such programs and how many students graduate per year.
[3] Graduates of master's level or equivalent in biochemistry, chemistry, electronics and chemical engineering, information and communications technology, mathematics and statistics, and physics.

Source: OECD; Quantum Computing Report; QURECA

Methodology



Methodology

Quantum technology player landscape, investments, and market sizing

— 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 QComms 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

— 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, QComms, and QS, as well as the speed at which technological challenges are resolved

Acknowledgments

Key contacts Full team

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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McKinsey & Company

Quantum Technology Monitor
April 2023
Design by Darby

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