Can Europe Catch Up with the US (and China) in Quantum Computing?

August 2022
By François Candelon, Jean-François Bobier, Maxime Courtaux, and Gabriel Nahas

BCG

BCG HENDERSON INSTITUTE

Boston Consulting Group partners with leaders in business and society to tackle their most important challenges and capture their greatest opportunities. BCG was the pioneer in business strategy when it was founded in 1963. Today, we work closely with clients to embrace a transformational approach aimed at benefiting all stakeholders—empowering organizations to grow, build sustainable competitive advantage, and drive positive societal impact.

Our diverse, global teams bring deep industry and functional expertise and a range of perspectives that question the status quo and spark change. BCG delivers solutions through leading-edge management consulting, technology and design, and corporate and digital ventures. We work in a uniquely collaborative model across the firm and throughout all levels of the client organization, fueled by the goal of helping our clients thrive and enabling them to make the world a better place.

The BCG Henderson Institute is the Boston Consulting Group's think tank, dedicated to exploring and developing valuable new insights from business, technology, economics, and science by embracing the powerful technology of ideas. The Institute engages leaders in provocative discussion and experimentation to expand the boundaries of business theory and practice and to translate innovative ideas from within and beyond business. For more ideas and inspiration, sign up to receive BHI INSIGHTS, our monthly newsletter, and follow us on LinkedIn and Twitter.

Contents

Executive Summary

After decades of research, quantum computers are close to becoming a reality. Several technological breakthroughs have been announced in recent times, and investments in the field reached an all-time high in 2021. The myriad benefits of quantum computing, from optimizing logistics networks to revolutionizing drug discovery, are knocking at our door.

If the European Union (EU) wishes to capture some of those benefits, it must improve its present position with regard to developing and using quantum systems. Other-wise, the EU will yield ground to the US and China, and lose the chance to become a technological powerhouse.

Current Position. Many countries are engaged in a global tussle for leadership in quantum computing. Becoming a leader will require achieving success on three fronts: support from government entities, commitment from private companies, and attention to developing talent. In this report, we will evaluate the major players' positions on these three dimensions to understand the EU's current and future status.

Our research indicates that the US is currently the front-runner, leading its peers on every dimension, especially in private-sector efforts. A trio of pursuers—the UK, China, and the EU—are well positioned too, particularly in terms of government support and talent pools.

The EU is among the leaders in public investment and has adopted robust plans, such as the European Commission's Quantum Flagship. But the US remains ahead in winning patents, setting up startups, and making investments, with China in hot pursuit. The EU is also among the world's leaders in producing talent, along with the US and China.

Emergent Risks. Although the EU appears strong, the reality on the ground is less positive, as the continent displays multiple symptoms that may portend trouble down the road.

First, the EU has scattered its efforts across the continent without forming an interconnected quantum ecosystem. Although the Quantum Flagship program is supposed to coordinate efforts, most countries on the continent continue to work in silos. Even at the national level, our analysis shows, European countries have not achieved the level of coordination between stakeholders and companies that countries such as the US and China have managed.

Second, the EU is creating a private sector with little or no ability to scale. The European nations lack the type of private investments that enable quantum computing startups to scale in the US, which is a venture capital powerhouse. Moreover, the EU lacks big digital players—such as Google, Amazon, and IBM—that have the power to consolidate the quantum sector.

Third, the EU has a people market that focuses on developing academic talent. Although the EU has almost as many top universities focusing on quantum computing as the US does, BCG estimates that the latter has two to three times as much talent at work in quantum technology businesses.

Ensuring the EU's Quantum Sovereignty. The EU, its member governments, and policymakers should immediately implement bold plans to tackle the emerging risks, acting on all three fronts to ensure the region's quantum sovereignty.

First, the EU should interconnect all quantum computing efforts by its member states and stakeholders at the European level. Success depends on governments' commitment to working together to advance the region's quantum computing capabilities. The EU must prioritize public intervention while aligning its ambitions and strategies across counties and stakeholders.

Second, the EU needs to foster the conditions necessary to develop a private sector that can scale. Its startups should not remain early-stage ventures indefinitely; instead, they should scale and become digital giants. Governments and policymakers will need to work together to tackle the EU's investment gap, especially in late-stage funding, while supporting the creation of a market for quantum computing applications by offering incentives to boost adoption by incumbents.

Third, the EU must create business-oriented quantum talent, ensuring that people leave academia and support the development of private quantum technology initiatives. Accomplishing this task entails developing the region's talent pipeline from end to end, and securing adequate funding for the purpose. Moreover, the EU must strive to become a magnet for international talent.

Only by tackling these challenges can the EU realistically hope to succeed in the quantum computing industry. Otherwise, the advent of quantum computing could sound the death knell for the EU's competitiveness and technological independence.

The Global Quantum Computing Race

> **Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy.**

— Richard Feynman, "Simulating Physics with Computers," *International Journal of Theoretical Physics*, 1982

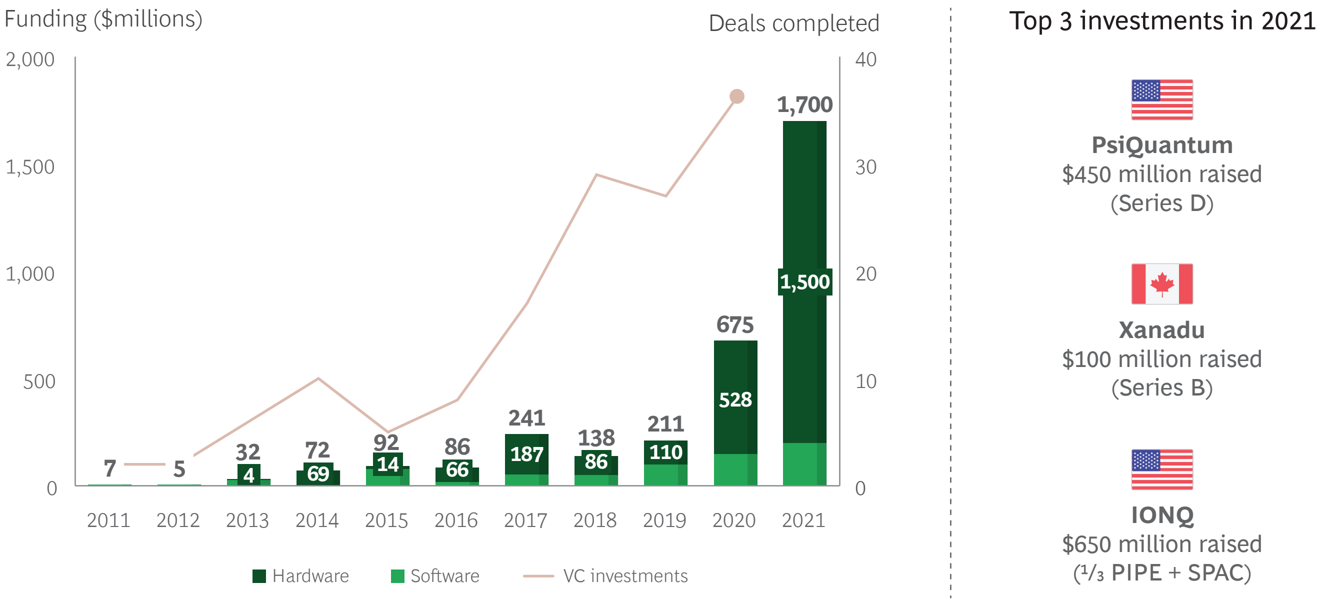
Humankind has never been as close as it is today to realizing the ideas of the American physicist, Richard Feynman (1918–1988). In a 1982 paper titled "Simulating Physics with Computers," Feynman postulated, among other things, that to solve specific categories of problems, we would need to build quantum computers. Like all deep technologies, quantum computing technologies, after a slow start, have matured rapidly in recent times. Consequently, the first quantum computers, which will be able to solve problems that are beyond the reach of traditional computers, could soon see the light of day.

There have been several breakthroughs in quantum computing in recent times. In October 2019, in a paper published in the science journal *Nature*, Google reported a milestone achievement. The American digital giant announced that its quantum computer, Sycamore, had solved in minutes a complex problem that would have taken the most powerful conventional supercomputers thousands of years to crack. By July 2021, the University of Science and Technology of China (USTC), based in the city of Hefei, claimed that it had solved a problem that was three orders of magnitude tougher than the one that Google's machine had tackled, and in September 2021, USTC announced that it had bested its own record by another three orders of magnitude.

November 2021 saw two more developments in quantum computing. The US's Quantum Economic Development Consortium revealed that a novel error-suppression method it had helped develop could increase the probability of success for quantum computing algorithms by 2,500%; and Stanford University engineers unveiled a simpler design for a quantum computer. Then, in June 2022, a Canadian firm, Xanadu, unveiled a quantum device, Borealis, that can outperform any supercomputer at one particular operation: delivering a series of numbers with a specified range of probability. Borealis can do so in just 36 millionths of a second whereas the same task would take today's supercomputers more than 9,000 years to compute.

Unsurprisingly, private-sector investments in quantum computing the world over have risen to record levels. In 2021, private investments in the equity of quantum computing firms increased almost tenfold over their level during the period from 2015 to 2019, according to BCG data. (See Exhibit 1.) Last year also saw the biggest sale ever of an equity stake in a quantum hardware firm, when the Anglo-American startup, PsiQuantum, raised $450 million to develop a general-purpose silicon photonic quantum computer. In fact, around three-quarters of the $1.3 billion of private equity investment in quantum computing firms since 2018 has been in hardware development. In addition, since 2013, governments have announced investments of over $20 billion to develop quantum computing systems.

Exhibit 1 - Acceleration of Investments in Quantum Computing



Sources: PitchBook; BCG analysis.

Note: PIPE = private investment in public equity; SPAC = special-purpose acquisition company.

Quantum Computers Will Disrupt the World While Creating Value

Undoubtedly, quantum computing possesses the potential to create enormous value in almost every industry, from automotive and aerospace to finance and pharmaceuticals. (See Exhibit 2.) The new machines could create fresh value of $450 billion to $850 billion over the next 15 to 30 years, according to recent BCG forecasts. We estimate that companies and governments could capture $5 billion to $10 billion of that value in just the next three to five years if the technology scales as fast as we expect it to.

Quantum systems will be able to tackle many kinds of computational problems, with the focus at present on complex applications such as machine learning, simulations, optimization, and cryptography.

Machine Learning (ML). Quantum systems will identify complex patterns from fresh data and use them to train sophisticated ML algorithms. That will accelerate the development of AI applications for autonomous driving, for example, as well as those for preventing fraud and money laundering.

Simulations. Quantum computers will be able to simulate processes that can be found in nature but are difficult to study with traditional computers. By doing so, they will transform drug discovery, battery design, and fluid dynamics, among other things, as well as derivatives and options pricing.

Optimization. Quantum algorithms will be able to identify the optimal solution to a complex problem among all the feasible ones. Companies can develop such applications to tackle problems in logistics and risk management, for example.

Cryptography. Quantum computing will crack traditional encryption protocols as well as make better encryption standards possible, as a team of BCG authors noted in a recent Fortune article.

Exhibit 2 - Quantum Computing Will Create Value Across Several Industries and Use Cases

	Applications	Private landscape Value creation potential ($billions)[1] Low	High
Cryptography ($40 billion to $80 billion)	Encryption/decryption	**40**	**80**
Optimization ($100 billion to $220 billion)	Aerospace: Flight route optimization	**20**	**50**
	Finance: Portfolio optimization	**20**	**50**
	Finance: Risk management	**10**	**20**
	Logistics: Vehicle routing/network optimization	**50**	**100**
Machine learning ($150 billion to $220 billion)	Automotive: Automated vehicles, AI algorithms	**0**	**10**
	Finance: Fraud and money laundering prevention	**20**	**30**
	High tech: Search and ads optimization	**50**	**100**
	Other: Varied AI applications	**80+**	**80+**
Simulation ($160 billion to $330 billion)	Aerospace: Computational fluid dynamics	**10**	**20**
	Aerospace: Materials development	**10**	**20**
	Automotive: Computational fluid dynamics	**0**	**10**
	Automotive: Materials and structural design	**10**	**15**
	Chemistry: Catalyst and enzyme design	**20**	**50**
	Energy: Solar conversion	**10**	**30**
	Finance: Market simulation (e.g., derivatives pricing)	**20**	**35**
	High tech: Battery design	**20**	**40**
	Manufacturing: Materials design	**20**	**30**
	Pharma: Drug discovery and development	**40**	**80**

Sources: Academic research; industry interviews; BCG analysis.

[1]Represents value creation opportunity of mature technology.

Quantum computing will create huge value in almost every industry, but it will pose an unprecedented threat to cybersecurity, too.

Quantum Computing Poses A Potent Cyber Threat

At the same time, the dawn of quantum computing will pose an unprecedented threat to cybersecurity. Hackers will be able to break through the security of almost every conventionally encrypted device or system by deciphering the public keys generated by the RSA cryptosystem. The threat will affect everyone, from individuals and institutions to companies and governments.

In addition to systems that store individual information such as personal and financial data, computer systems that are central to national security—such as military systems, police networks, hospital systems, internet, telecommunications, and mobile networks, energy systems, and banking and finance networks—will become easy targets. Unless governments develop quantum computing capabilities, they won't be able to protect themselves or respond to attacks by quantum hackers.

With quantum computing likely to pose an unprecedented cyber threat in the near future, quantum cryptography and communications have emerged as possible responses to counter that threat. New networks and protocols will protect business and government by enabling quantum key distribution, which uses the principles of quantum physics to randomly distribute keys between users over a network of optical links. Several initiatives have emerged worldwide. China, which launched the first quantum-enabled satellite in 2016 to ensure secure data transmission, has created what is currently the longest quantum key distribution network, which extends from Beijing to Shanghai.

Every Nation is Rushing to Embrace the Quantum Future

Most countries aren't adopting a wait-and-watch approach to an impending Cyber Armageddon. Several governments, with the US and China leading the way, have unveiled quantum computing development strategies over the past decade, especially in the past five years. (See Exhibit 3.) They are acting quickly and making large investments to gain leadership of the field of quantum computing.

Specifically, in December 2018, the US Congress passed the National Quantum Initiative Act, which described the US's quantum computing strategy, prescribed the national response, and invested over $3 billion in quantum computing initiatives. Similarly, China's government has invested over $10 billion to build the world's largest quantum research facility in the city of Hefei. Other countries are forging alliances with the leaders in the quantum computing race. For instance, in 2021, Australia, the UK, and the US signed the AUKUS alliance, a pact that focuses on developing new technologies rather than defense capabilities, with the three nations sharing their technological advances in fields such as AI and quantum computing.

Like the US and China, the 27 member states of the European Union (EU)—on which we will focus in this report—have to participate in, invest in, and try to win the quantum computing race if they wish to secure Europe's future competitiveness and sovereignty. After all, quantum computing seems likely to disrupt several of the EU's key manufacturing industries, such as aerospace, automotive, chemicals, defense, electrical, pharmaceuticals, and textiles, as well as its service sectors, such as banking and financial services. For the EU, it's now or never, making today its Quantum Moment.

Exhibit 3 - The EU's Competitive Start in Quantum Computing

2013

- The UK creates a National Quantum Technologies Program, investing $300 million

2016

- China launches its 13th five-year plan, with projects for quantum computing and communications; announces an investment of $10 billion in 2017

2018

- The EU sets up the Quantum Flagship program, investing $1.1 billion
- The US passes the National Quantum Initiative Act, investing over $1.2 billion

2019

- France creates a National Agenda on Quantum Technologies with a seven-year investment of $700 million
- Israel allocates $400 million over six years

2020

- Japan allocates about $270 million to a quantum roadmap
- Russia announces an $800 million investment

2021

- Australia invests $100 million
- Canada announces an investment of $400 million over seven years
- France announces a $1.1 billion investment plan
- Germany unveils its Quantum Computing Roadmap, with a $2.2 billion investment

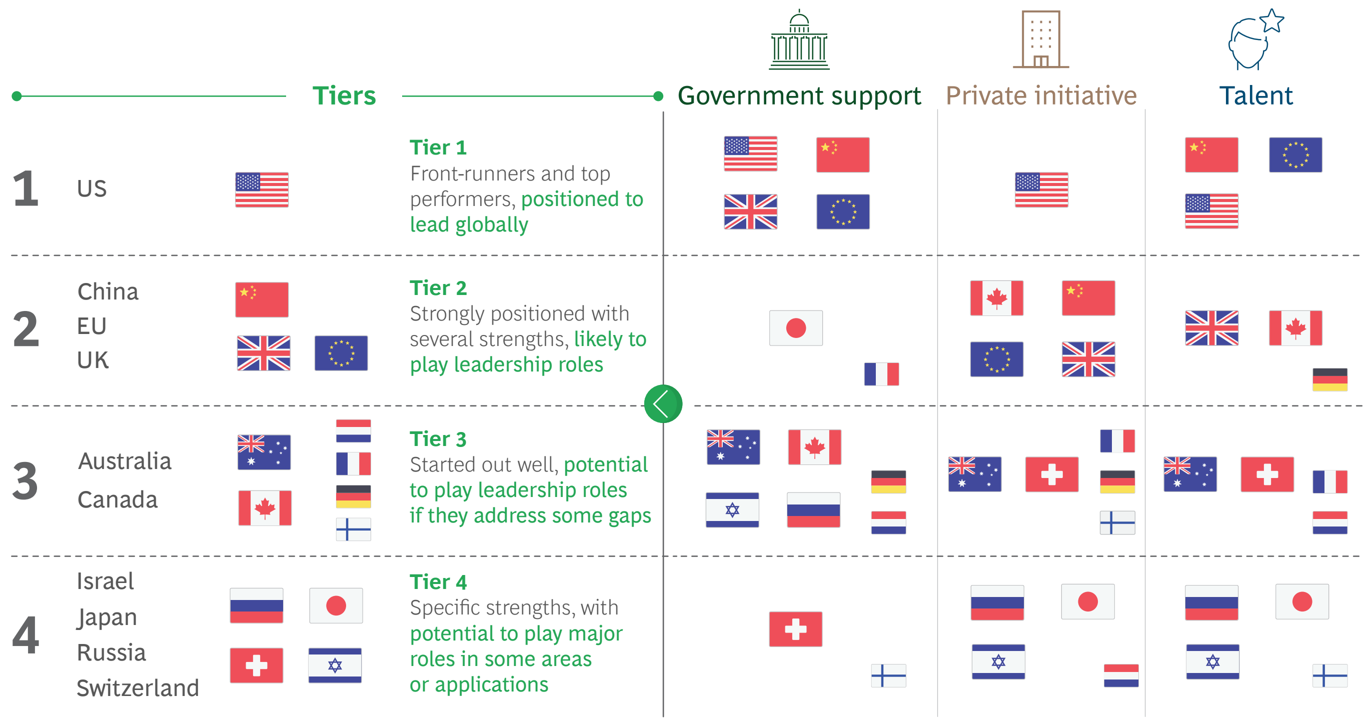
Sources: Literature search; BCG analysis.

Assessing Europe's Chances

It may not be easy for the EU to win the quantum computing race or to gain quantum sovereignty, although such an outcome is eminently possible. Developing and controlling the latest advances in this field will require a continent-wide effort, supported by governments and public institutions, the private sector, and a vast amount of talent. In this report, we will highlight the positions of the world's key players on those three dimensions in order to gauge the EU's current status in quantum computing. We will focus on the EU's policies, actions, and efforts as a whole, as well as on the individual actions of EU member states—in particular, Finland, France, Germany, and the Netherlands—that are trying to develop quantum computing systems.

At the outset, our analysis suggests that the US is the global front-runner in quantum computing, outpacing its peers on every dimension, especially in terms of private-sector efforts. The EU is well positioned among a troika of second-tier challengers to the US, along with China and the UK, having garnered a great deal of public-sector support and having begun to develop the necessary talent. Even so, the EU appears to be a major contender only because of the combined efforts of all its members. Considered on their own, not one of the countries in Europe would be a front-runner in the quantum computing race—yet. (See Exhibits 4 and 5.)

Exhibit 4 - The 2022 Quantum Computing Country Rankings



Source: BCG analysis.

Note: The smaller flags in this exhibit represent individual EU countries and show where they would appear if they were considered by themselves. Throughout this report, we evaluate the EU in terms of the aggregate actions of its individual members as well as of EU central policies.

Elsewhere, Canada and Australia have positioned themselves as midlevel contenders in the quantum computing sweepstakes, developing capabilities in many key dimensions. Canada, for instance, is a front-runner in private-sector investments in quantum computing, going head-to-head with the US, and its start-ups include Xanadu, which hopes to deliver quantum error correction by 2030. Australia, meanwhile, has initiated concrete plans to develop talent in the field. Finally, countries such as India—which has invested over $1.2 billion in quantum technology development since 2020—Israel, Japan, Russia, and Switzerland have launched quantum computing projects, setting ambitious targets but trailing the front-runners in implementation.

Let's analyze the positions of the main contenders in quantum computing and how they measure up on three critical dimensions.

Government Support. National and local governments can support the development of quantum computing by funding those efforts and by framing supporting policies such as a national quantum computing strategy.

China is by far the global leader in public investment, having spent approximately $10 billion to create a national laboratory for quantum information sciences. (See Exhibit 6.) Usually outspent in public investment, the EU is trying to keep pace by allocating $6.5 billion in 2021 for quantum computing investments, which is more than double the $3 billion that the US government has budgeted for. But while the EU is at the forefront in public investment, its focus differs from that of its peers, with most of its financial support going to academic institutions and research efforts rather than to state-sponsored initiatives.

Exhibit 5 - The Three Dimensions of National Success in Quantum Computing Efforts

Government support

Strategy and coordination
- National targets
- Quality of plans and roadmaps
- Power of central governance
- Involvement of military and intelligence agencies

Quality of support
- Amount of government investment
- Levers

Private initiative

Private investments
- Amounts
- Maturity (financing rounds)
- Capacity to retain national investments

Business landscape
- Number of companies
- Number of employees
- Company valuations

Value chain leadership
- Number of patents
- Size of quantum market
- Size of quantum applications market

Talent

Education ecosystem
- Number of top universities
- Number of students
- Number of articles published

Quality of support
- Policies

Talent ecosystem
- Amount of talent

Type of analysis: Qualitative Quantitative

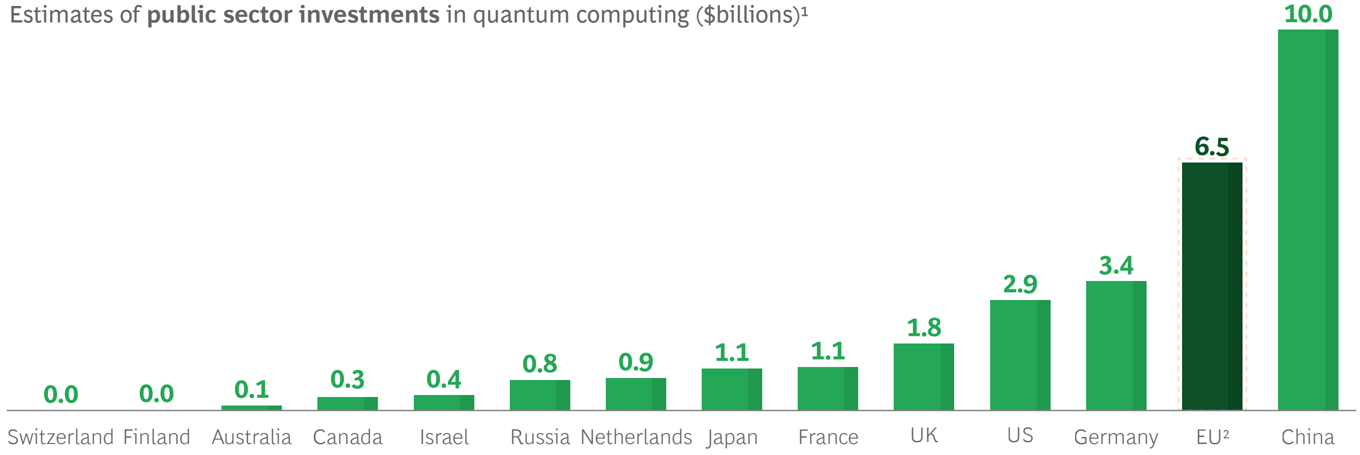
Source: BCG analysis.

Direct funding isn't—and shouldn't be—the only lever by which governments can realize their quantum computing ambitions. Australia and Switzerland haven't set targets or created roadmaps, whereas the EU and the US have developed plans to guide the evolution of their quantum computing ecosystems.

By way of illustration, in 2018, the US National Quantum Initiative Act created a national plan for quantum computing and provided a framework to help coordinate efforts by US federal agencies. This law has allowed the US to set up new quantum research centers, foster international collaboration programs with nations such as Japan, and create educational partnerships with American digital giants such as Google. The US has even enacted export controls to block quantum technologies from being exported, although experts debate whether doing so was premature.

Concrete plans provide teeth to national strategies. While the US is creating shared facilities such as research centers and is developing use cases through public agencies and partnerships with business players, the EU is focusing on research and collaboration between universities through the European Commission's Quantum Flagship program. Launched in 2018 with €1 billion in funding, the Quantum Flagship is one of the EU's largest and most important research and innovation projects. It coordinates research across several quantum computing domains, creating groups of industry stakeholders and running educational pilots. Well received by experts, the Quantum Flagship has turned into a dynamic mechanism that fosters collaboration between European countries. Its project calls and initiatives could well stimulate the creation of a robust quantum computing ecosystem on the continent.

Exhibit 6 - Ranking Countries by Government Investments in Quantum Computing



Sources: Literature search; BCG analysis.

[1]The data in this exhibit represents public announcements made after 2013; investments may be made for different time horizons.

[2]Investments made centrally by the EU (~$1.1 billion) as well as those made by Germany, France, the Netherlands, and Finland.

Other digital powerhouses, such as Japan and Israel, have developed only embryonic plans in the field of quantum computing. In 2019, the Israeli government allocated $350 million to quantum computing, but it didn't draw up any concrete plans to develop systems. Similarly, Japan incorporated quantum computing in a moonshot R&D national program in 2020, hoping to develop a fault-tolerant universal quantum computer by 2050. Other than funding a few research projects, though, the government has taken few follow-up actions.

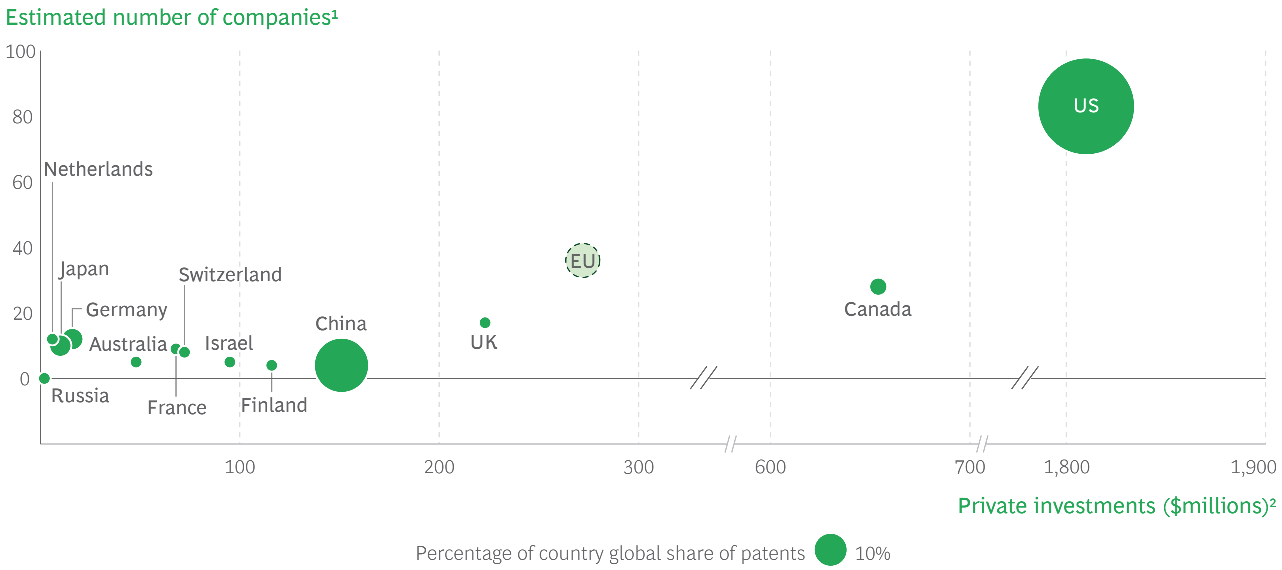
Private Initiative. Companies and startups will be key elements in the development of quantum computing systems, translating quantum research into products and services that will generate value in other industries. The US's dominance on this dimension is indisputable because of the large investments in American startups in the field. Only the EU and Canada rival the US in the number of companies working in the area. Here, too, the EU is well positioned in terms of its aggregate efforts, but none of its member states come close to the US.

The US boast the largest number of companies operating in the field, and its startups attract most of the investments in quantum computing. (See Exhibit 7.) The US has witnessed some of the biggest deals in quantum computing, and the government is relying on the country's digital giants, such as IBM and Google, to push the technological envelope. For instance, IBM crossed the 100-qubit barrier last year, unveiling a 127-qubit microprocessor, and it hopes to develop a 1,000-qubit chip by the end of 2023.

Meanwhile, China is trying hard to catch up with the US by winning as many patents as possible. It has registered the second largest number of quantum computing patents in the world since 2000, behind only the US. China, too, relies on its large digital firms to maintain its momentum in quantum computing. For instance, Tencent has set up a dedicated quantum lab to connect theory with practical applications. In 2020, the company announced an investment of over $70 billion in its computing infrastructure, particularly for developing quantum technology. Tencent isn't China's only private-sector quantum computing player, however. Alibaba developed an 11-qubit machine for quantum cloud computing by 2018, and Baidu currently offers a platform that companies can use to build neural network models for quantum applications.

The US is the front-runner while the EU appears to be well positioned, along with China and the UK, but no EU country is a leader on its own.

Exhibit 7 - The US Has the Most Startups, Private Investments, and Patents in Quantum Computing



Sources: PitchBook; Crunchbase; BCG analysis.

[1]The data in this exhibit excludes Big Tech companies (e.g., IBM, Google, and Tencent), whose focus is not solely on quantum computing.

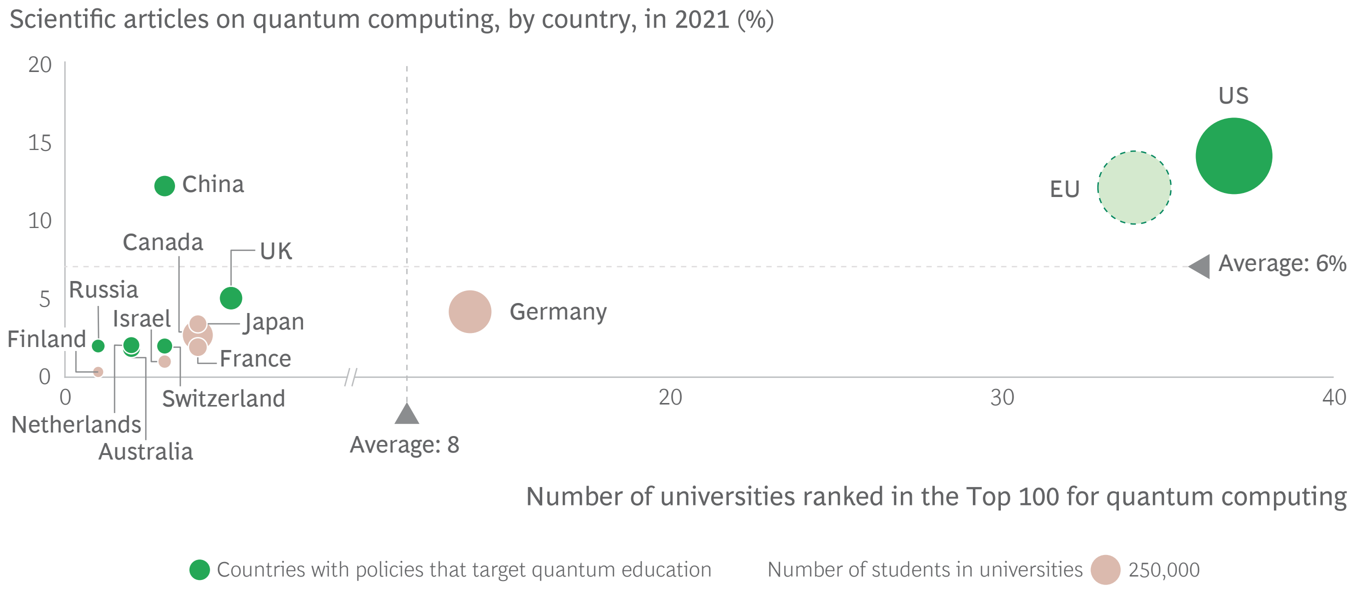
[2]Deals since 2010 in nonpublic companies that focus on quantum systems.

Talent. A talent ecosystem is essential for developing a quantum computing industry. The EU and the US are front-runners in this regard, encouraging their top universities to focus on quantum computing and the publication of scientific articles on the subject. (See Exhibit 8.) They are nurturing their ecosystems to meet the challenge of supplying the next generation of quantum computing business talent.

The EU has recently upgraded its learning ecosystem with several pilot programs. For example, it has set up a QTEdu Open Master Pilot to help students across Europe benefit from the quantum computing expertise of more than 30 educational institutions on the continent. Similarly, the US has created the National Q-12 Education Partnership with leading digital companies to create content and to conduct outreach initiatives in middle schools and high schools to broaden society's access to quantum computing knowledge.

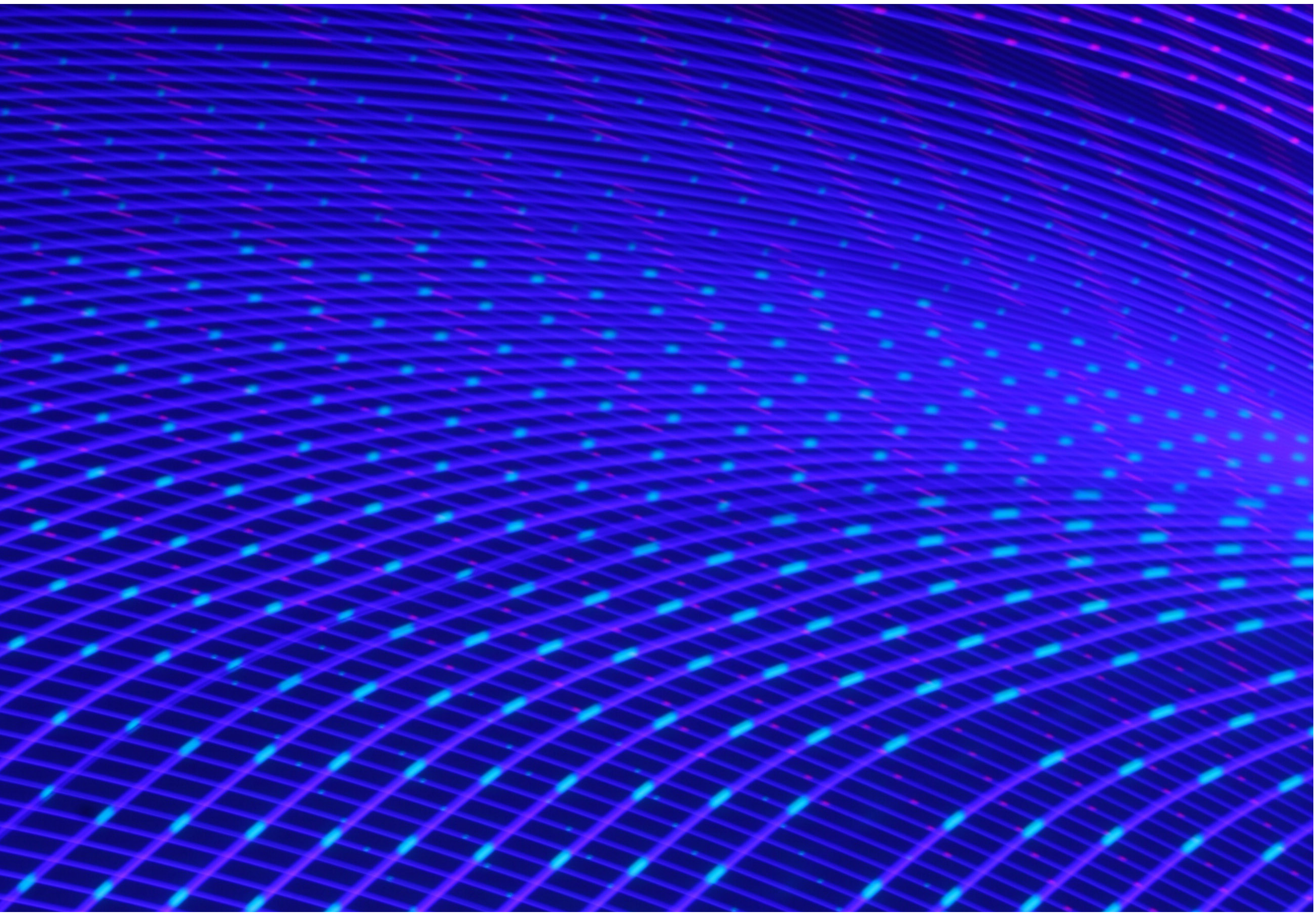
Other countries are trying to develop quantum computing talent rapidly, too. Switzerland is accelerating its universities' efforts by creating a master's program in the subject rather than offering only doctoral programs. And the Australian government has backed the creation of the Sydney Quantum Academy, a partnership of four national universities, to foster a talent ecosystem. The universities support end-to-end development of the pipeline, offering summer school courses in quantum theory for high school students, funding research by undergraduates and doctoral degree candidates, and assisting in placement through internship programs created in partnership with companies such as IBM Australia.

Exhibit 8 - The EU Is Second Only to the US in Scientific and Educational Capabilities



Sources: EduRank; Web of Science; Literature search; BCG analysis.

Note: The number of articles and universities for the EU represents the sum of the individual totals for each EU country.



The EU's Rising Risks

On paper, the EU may appear to be globally competitive in quantum computing, but the reality on the ground is somewhat different. The telltale signs become obvious in a comparison of the EU's advances in quantum computing with the corresponding advances of other nations. For one thing, the EU relies on foreign companies for its quantum computing capabilities; for example, in 2021, Germany had to procure a quantum computer from IBM for research.

The EU may have in place all the ingredients for failure, rather than success, as has been the case with technological shifts in the past. For example, Europe failed to become self-reliant in semiconductors because, although its academic institutions conducted great research, the region did not foster a private sector that could develop and scale the business. As a result, the EU could control only certain parts of the global supply chain, most of them R&D-intensive efforts such as producing semiconductor-making equipment. The long-term result was increased EU dependence on companies from mainland China and Taiwan for chips. Recently, as a last hope, after several years of inaction during which the gap between it and the market leaders continued to widen, the EU enacted the EU Chips Act—a capital-intensive program to attract semiconductor manufacturing capabilities to the EU.

As the case of the EU's semiconductor industry vividly demonstrates, government support and world-class R&D are insufficient to secure sovereignty in an emerging technology. The EU is again in danger of missing the tipping point from R&D to adoption at scale in the quantum computing sector. Its global rivals have combined private and public capabilities to make advances in several areas, but as yet the EU hasn't been able to do so.

While American companies and Chinese researchers have achieved quantum supremacy, the EU's players lag behind. For example, IQM, one of the better-known quantum startups in the EU, commissioned Finland's first quantum computer last year, but with a capability of just 5 qubits. Even its ambitions don't compare with those of its global rivals; IQM hopes to build a 50-qubit machine by 2024 while Google plans to develop a 1-million-qubit superconducting system by 2030!

The EU is behind in quantum communications, too. In 2016, China launched the world's first quantum satellite; and in 2019, it established an integrated quantum communications network, connecting two satellites to fiber-optic cables on the ground. USTC has made strides in quantum communications as well. It has been operating the world's largest quantum network, connecting banks, universities, and government offices in Hefei. Similarly, the US Department of Energy has laid out a blueprint for the country's quantum internet. Both nations have created quantum key distribution networks at scale; the US has built a 500-mile-long network, and China has built one that is three times as long.

These developments offer a taste of what the future will look like if countries continue on their current trajectories. Prototypes of a 100-qubit quantum computer and a quantum communications network may not be usable today, but developing them provides the foundation on which countries can build their quantum computing industries. If the EU can't meet the challenges of coordinating quantum computing efforts across the continent, developing a private-sector quantum computing industry, and growing its talent quickly, it risks losing the quantum computing race. To be sure, the outcomes aren't clear yet, but losing to its global rivals in this sunrise sector would pose a serious threat to the EU's competitiveness in the long run.

Uncoordinated Efforts and a Disconnected Ecosystem

Although the EU launched its decade-long Quantum Flagship program in 2018 with the goal of coordinating efforts across the continent, many member states continue to work on quantum computing in silos. In 2021, Germany and France rolled out national roadmaps and plans, each embodying a different approach, without leveraging the synergies between them.

France is executing a fairly decentralized €1.8-billion plan managed by several research institutions, with specific allocations for areas such as quantum computing, quantum communications, and quantum sensing. In contrast, Germany has chosen a highly centralized approach, apportioning €2 billion in funding under the management of the ministries of research and economic affairs. The ministries don't focus on key technology areas, but each plays a different role: the ministry of research funds research and identifies potential applications for quantum computing, while the ministry of economic affairs forms industrial consortia and creates industry innovation centers.

Despite the obvious differences in the two approaches, France and Germany share the common goal of developing national quantum systems, which should generate synergies at several levels. Unfortunately, the two countries have not explored avenues for collaboration such as developing a shared infrastructure to gain scale, performing joint funding calls to optimize resource allocation, and creating transnational consortia to exchange best practices.

In general, the EU's member states have not matched the coordination displayed by stakeholders in other countries. For example, the US has tasted success in using its military's efforts in quantum computing to kickstart civilian initiatives. Rather than relying solely on agencies such as DARPA and NASA, which have traditionally taken the lead in developing new technologies, the US Department of Defense, the CIA, and the NSA have all invested in efforts to develop quantum computing technologies. The CIA has even set up In-Q-Tel, a venture capital fund that invests in deep technologies such as quantum computing.

Moreover, the US government is quietly coordinating the activities of its quantum ecosystem and ensuring, for instance, that companies work with one another. It has funded QED-C, a consortium of private companies that promotes cooperation in quantum computing by driving discussions on possible applications and hosting workshops to discuss priorities and roadmaps.

By contrast, after some promising steps—such as the French Innovation Defense Agency's funding of the quantum computing startup, Pasqal—there has been almost no military interest in quantum computing in the EU. At the corporate level, EU companies are struggling to join forces and move beyond their solo efforts. As one of Europe's leading investors in quantum computing confessed: "Even though the European quantum ecosystem is quite small, companies don't know each other and cannot generate synergies." The consequences of insularity could be catastrophic. If the EU cannot consolidate its member-states' efforts, stakeholders, and companies, it will end up with a disconnected ecosystem that can't generate the synergies that will be necessary to develop and scale quantum computing quickly.

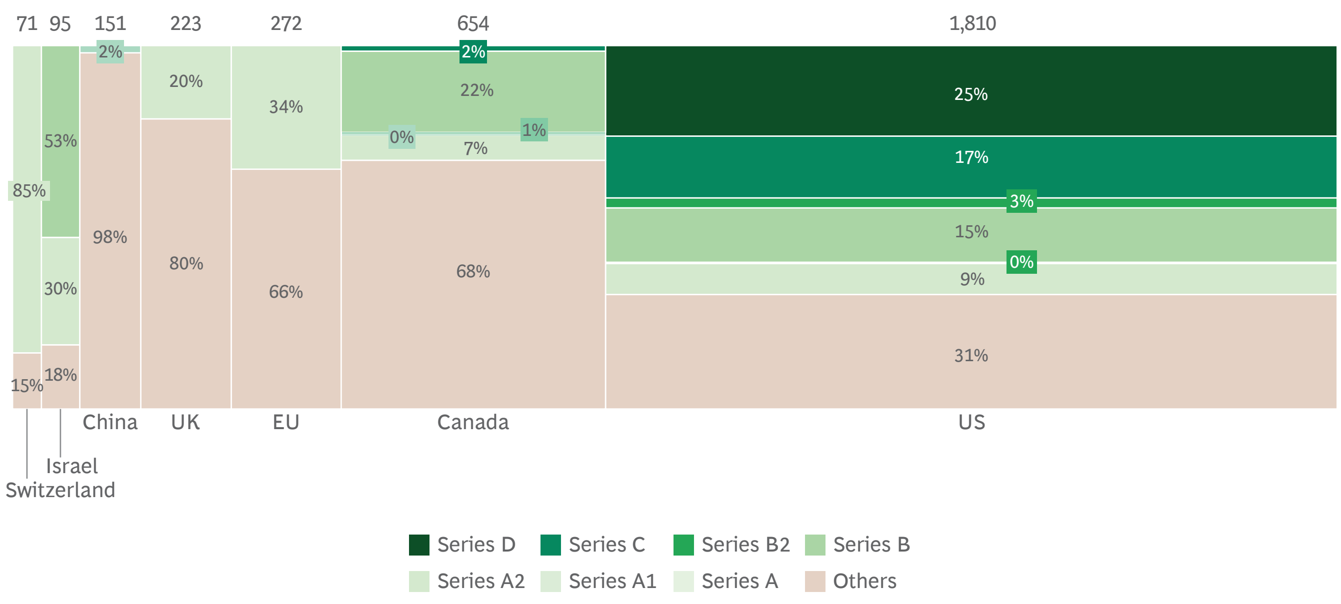
The EU's Quantum Business Can't Scale

The EU's quantum computing ecosystem is far from mature today because of the region's focus on academia, its lack of business involvement, and its fractured quantum computing ecosystem. The EU has created a pipeline of promising startups, but the ecosystem must mature if those startups are to successfully scale, and not collapse the moment they go head-to-head with tech giants from abroad.

Several factors contribute to the EU business ecosystem's lack of maturity. First, compared to powerhouses like the US, European countries and companies don't have the level of VC investment necessary to scale their quantum computing startups. The US attracts much larger amounts of seed capital as well as more rounds of financing. (See Exhibit 9.) Since 2010, for instance, American VCs have invested approximately $1.8 billion in quantum computing startups, a quarter of which has taken the form of Series D funding. On the other side of the Atlantic, EU startups have attracted barely $300 million, with almost no investments in Series C or Series D funding.

Exhibit 9 - The US Attracts the Most Quantum Computing Investments and the Most Rounds of Financing

Value of deals in quantum companies per series round since 2010[1] ($millions)



Sources: PitchBook; BCG analysis.

Note: Values for Russia, Japan, and Australia are not reported in this exhibit, as each of them represents less than 1% of total investments. Values for Finland, the Netherlands, Germany, and France are not reported separately from their contribution to the total given for the EU.

[1]Nonpublic companies.

Second, the EU's policies restricting foreign investment in quantum computing stem from a desire to ensure self-sufficiency, but they may do more harm than good. The laws have also discouraged investors on the continent, who regard foreign firms as more attractive investment opportunities because of their ability to attract capital from bigger funds, especially in the US. Although the US has similar policies, such as those overseen by the Committee on Foreign Investment in the United States to restrict foreign investments, it has drawn 25% of its investments from EU-based funds, according to BCG estimates. While quantum computing startups in the EU have attracted less than 2% of their investments from US firms, Canadian startups have generated around 20% of their investments from US firms. Countries such as China have managed to attract local investors, too, retaining more than 80% of the investments made by domestic funds. (See Exhibit 10.)

Third, unlike the US, the EU lacks big players that possess the financial power to scale and consolidate the quantum computing industry. For instance, Microsoft was one of the leading investors in PsiQuantum two years ago, investing more than $215 million in the Anglo-American startup. But the EU's companies, even its manufacturing giants, are unwilling to match investments at that scale. Bosch, for instance, participated in two rounds of investment in two EU quantum computing companies, IonQ and Zapata, but its investments added up to just $70 million.

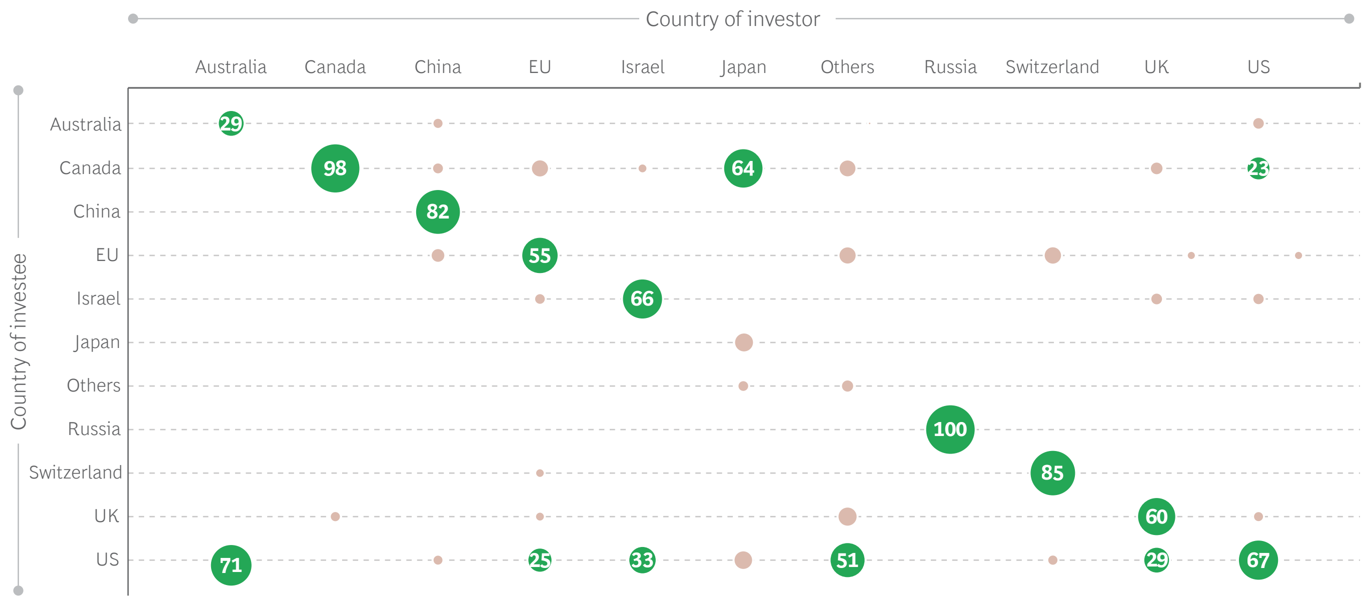
The Limits of the EU's Academic Talent

Undeniably, the EU has developed world-class academic capabilities in quantum computing research and education. The EU is the world's second biggest publisher of scientific papers on the topic, behind only the US, contributing around 15% of such articles every year. It has also developed strong educational capabilities. Altogether, 34 of the top 100 universities in the world for quantum computing are located in the EU—a number that is quite close to the US's 37. Nevertheless, the EU has struggled to transform its academic talent into business stars. It has about one-third as many users with quantum skills than the US on LinkedIn, and roughly half as many employees in quantum computing startups.

Moreover, the few quantum engineers who work in the EU's private sector are at risk of being poached by the US's digital giants. The shortage of talent at the intersection of quantum theory and business practice prevents European startups from growing and underscores how few people have the ability to make informed investment decisions in the field, limiting the EU funds' expertise in quantum technologies. BCG identified more than 232 venture funds in the US that have some degree of expertise in quantum computing investments; in contrast, only 88 funds in the EU have invested in a quantum startup.

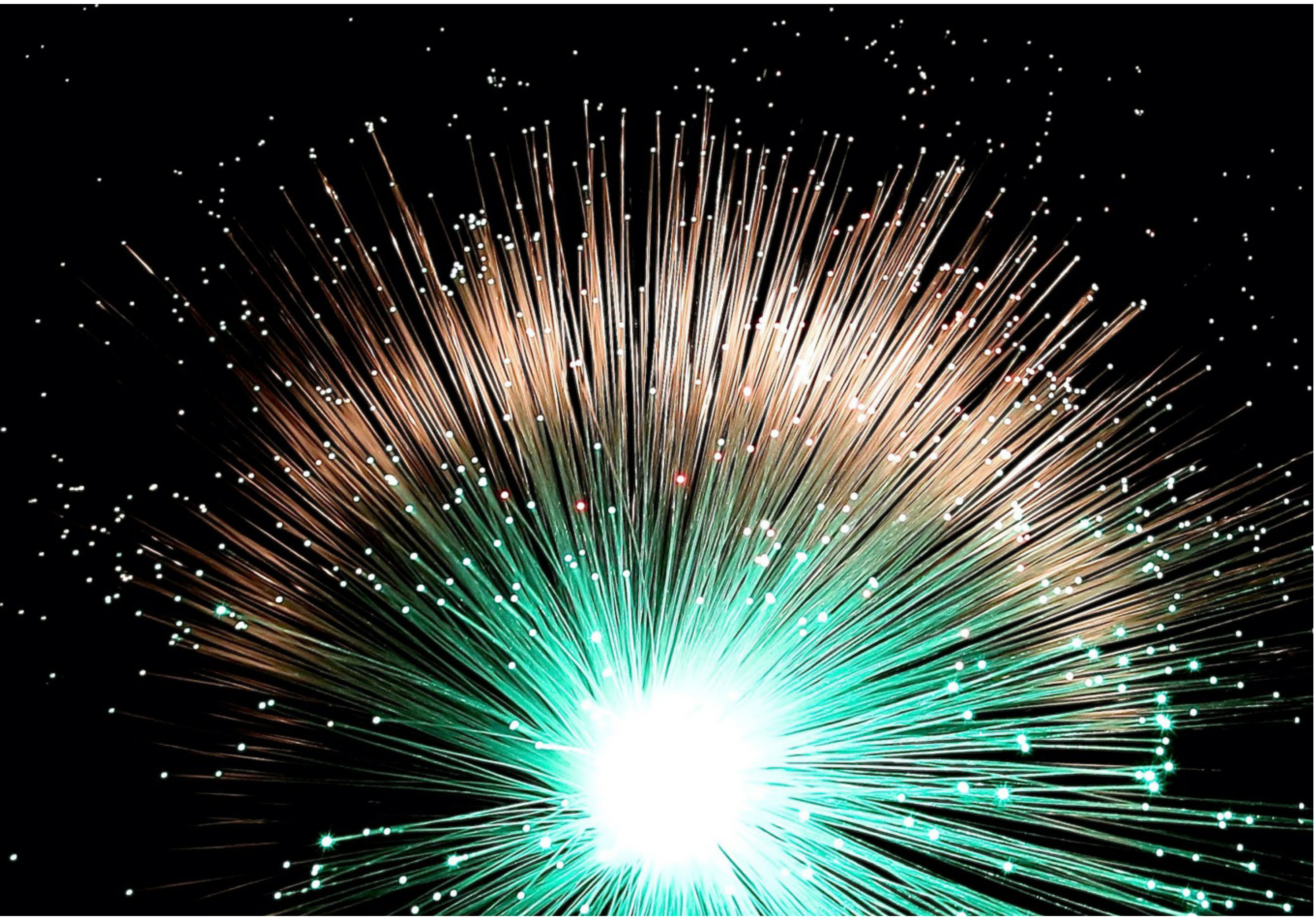
Exhibit 10 - The EU Struggles to Attract Investment in Quantum Computing

Private investments by investor and investee country (%)



Sources: PitchBook; BCG analysis.

Note: The data in this exhibit represents investments since 2010 for which investors were disclosed and whose country could be determined. Only percentages larger than 20% are highlighted.



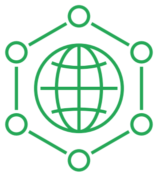
Ensuring the EU's Quantum Sovereignty

Despite the obstacles involved in coordinating public efforts, creating a private sector, and developing the talent for quantum computing, the EU still has time to carve out a strategy that might empower it to lead the field. To do so, however, the EU must act at once because rival nations are moving rapidly and making advances that will enable them to create quantum computing sectors and rapidly deploy quantum applications at scale. The EU, its member states, and its policymakers should act in unison on three fronts to secure its quantum sovereignty. (See Exhibit 11.)

The EU Must Connect Its Efforts

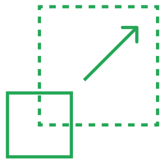
The EU can win the quantum race only if its member countries work together to advance its quantum capacity. In our assessments, France, Finland, Germany, and the Netherlands, although active in quantum computing, haven't achieved a great deal of maturity in the field individually. Only by working together can they develop the necessary capabilities to take on countries such as the US, China, and the UK. The EU must take action on two fronts: prioritizing public intervention and aligning strategy with ambition.

Exhibit 11 - The EU Must Use Three Levers to Get Ahead



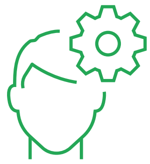
Interconnect efforts in Europe by...

- Aligning ambitions and strategies across member states and stakeholders
- Ensuring prioritization of public intervention



Scale private quantum computing sector by...

- Bridging the investments gap
- Developing the EU quantum market



Develop business-oriented quantum talent by...

- Building a talent pipeline
- Becoming a magnet for global talent

Source: BCG analysis.

Prioritize public intervention. The EU needs to be laser-sharp when investing in quantum computing. Although the Quantum Flagship initiative defines the EU's priorities in the short, medium, and long terms and specifies target areas of research, there is still too little clarity about how much investment should be allocated to each priority and which stakeholder should lead the ecosystem in tackling each priority.

When developing strategic plans and allocating funds, the EU must keep in mind the short- and medium-term gaps—such as in communication networks and superconducting computers—that are evident on the continent compared to in China and the US. The EU, through its core institutions, can coordinate or even pool the investments that its member states have made in quantum computing and offer them a coherent focus.

The EU still has the opportunity to become a trailblazer by creating an infrastructure sandbox that all of its stakeholders can leverage, especially as quantum science moves from theoretical to applied research. Controlling the physical hardware will be essential, giving each nation the ability to develop use cases in different industries. Sharing assets will be a potent innovation multiplier in the EU. France has started the movement internally, recently launching a program to link quantum machines and supercomputers so that they become available to every French researcher and company in the field. Similarly, the Netherlands has created Quantum Inspire, a computing platform that provides the country's users the hardware to perform quantum computations.

Align strategy with ambition. The EU must ensure that all of its member states and stakeholders collaborate to attain their common goal of European sovereignty in quantum computing. First, all members of the EU should be involved in making decisions, allocating resources, and defining priorities in quantum computing. Like the US, the EU could create a coordination office in its Quantum Flagship program to oversee the activities of the various agency, civilian, and military players in the field. Currently, the Quantum Flagship program's coordination team consists of just seven members, mainly from companies and universities, without any representation of other stakeholders such as national science ministries and research agencies.

Second, the EU must catalyze connections. Its governments and policymakers should work to create bridges between stakeholders by supporting dedicated accelerators and incubators. In the US, for instance, the University of Chicago created the first accelerator for early-stage quantum startups by working with a US Department of Energy laboratory. Similar initiatives in the EU offer valuable lessons. The Netherlands, for instance, has created QuTech, which aims, in partnership with Delft University, to develop prototypes of a quantum computer that can be scaled across the continent.

Finally, the EU must ensure cooperation among military and civil stakeholders because quantum technologies will disrupt both realms. Such cooperation will also serve as a strategy for attracting more funds to develop quantum systems. Military agencies must be involved in coordination efforts, and funds should be dedicated to military applications of quantum computing. For instance, the European Commission has created the European Defense Fund, which supports defense-related R&D by companies and research institutions, with priorities defined in cooperation with the EU's members. The EU could also create or participate in funds dedicated to emerging technologies. For example, in 2022, NATO set up a €1-billion innovation fund for emerging technologies, such as quantum computing. But key European countries, such as France, aren't involved in critical components of the initiative. If the EU wants to fight for a global quantum advantage, it must treat international and military cooperation as a priority.

The EU Must Scale Its Private-Sector Quantum Efforts

The EU needs to set conditions that will produce a private-sector ecosystem that can spawn and scale quantum computing startups. First, the EU must bridge the investment gap to ensure that the resources for scaling become available. Second, the governments of EU member states must develop a European market for quantum systems by becoming the first customers and by putting incentives in place to boost their adoption.

Bridge the investment gap. Surprisingly, the EU holds its own in the creation and financing of quantum computing startups. In addition to developing a pipeline of startups, the EU has seen the floating of dedicated VC funds such as Quantonation, an investment fund dedicated to financing early-stage quantum computing startups. But creating venture funds and private equity firms that focus on late-stage funding in the EU must become a priority.

To attract more investors to fund the scaling of quantum technology firms, governments should offer them financial support. Government support for scaling quantum technology firms could mimic the initiatives of the pan-European fund of funds, which the EU created to catalyze the creation of ten digital giants on the continent, and of the EU Chips Act, which recently created a €250-million public investment fund that could attract another €1.2 billion from private equity funds. Unless the EU can secure late-stage funding, promising European quantum computing startups such as IQM and Pasqal will be acquired by US or Chinese digital giants—or just die.

One additional challenge is the barrier that the EU has erected against foreign investment. As we noted earlier, the EU attracts less than 2% of overall investment in its quantum computing startups from the US, whereas Canada has attracted around 20%. Policymakers need to create workarounds to make European startups more attractive and accessible to investors from outside the region even while maintaining their European identity. For example, preauthorizing foreign funds to invest in startups or setting up a streamlined and simplified screening process would help the EU attract investments without losing control. Just as the EU has created EuVECA—a designation that prequalifies foreign fund managers and spares them the costs of authorization and compliance—it could create a status for sensitive sectors, such as quantum computing, to simplify foreign investment in EU startups.

The EU could look for inspiration from other technology-related policies that it has adopted, and create an exceptions regime to fund quantum startups in its member states. Introduced by the EU Chips Act, the mechanism is designed to offer government grants on a case-by-case basis to help scale innovative chip manufacturing technologies. A similar mechanism could help companies that are trying to move from engaging in quantum research to developing quantum applications that will help commercialize the technology on the continent.

Develop a quantum market. Developing quantum technologies in computer labs alone won't help the EU become competitive. The region also has to develop a vibrant market for applications of quantum technologies.

Government institutions and public-sector bodies can support quantum startups in the EU by becoming their first customers. This practice is not unprecedented. In the US, for instance, budgetary provisions require that at least 23% of the Department of Defense's spending be awarded to small businesses. In the same way, European governments should support the transition to a quantum-powered EU. The initial uses of quantum computing applications might include safeguarding critical national data through quantum protocols and developing national quantum computing networks for each country's researchers. The EU can look to EuroHPC JU, a joint undertaking that aims to deploy eight supercomputers across Europe, as a role model in setting up and scaling similar initiatives for quantum systems.

The EU's policymakers need to create economic incentives for incumbents to invest in quantum technology applications. Because the EU lacks large digital companies, national incumbents must play a key role in supporting and scaling the quantum ecosystem. Tax credits or preferential loans for companies that purchase EU-made quantum products and services will incentivize the continents' incumbents to position themselves at the forefront of using the technology. For instance, France's Crédit Agricole has announced a partnership with two quantum startups in the EU, Pasqal and Multiverse Computing, to apply quantum computing to financial applications.

Finally, the EU can help reduce the risks that incumbents face when investing in quantum systems. Governments and public institutions on the continent can ensure that first movers aren't at a disadvantage by developing a quality label for quantum startups akin to the one proposed two years ago for high-risk AI applications. Governments should also encourage investment in quantum computing systems by creating initiatives to connect the links in the ecosystem, as the EU did in the case of Scale Up for Europe. In addition, acting in concert with its member states, the EU should create a desk in Brussels to manage the relationship between private stakeholders and quantum researchers.

The EU Needs Business-Oriented Quantum Talent

The talent that necessary to develop quantum technologies isn't a challenge in the EU at present, but it is likely to become a bottleneck in the future. According to BCG estimates, building each fault-tolerant quantum system will require about 4,000 applied scientists and hardware engineers. Currently, however, the EU has only about 500 employees working in its quantum computing startups, and not all of them work in technical areas.

Given the magnitude of the difference between supply and demand, investing in creating quantum talent should be a top priority for the EU. The EU needs to create not only additional academic talent—an area in which it is already strong—but also business-oriented talent capable of working in tomorrow's quantum businesses. The EU must ensure that it establishes a strategy to develop an end-to-end talent pipeline while also becoming a magnet for quantum talent from overseas. Other countries, especially Australia and the US, are doing the same, but no country has deployed these efforts at scale yet. That gives the EU an opportunity to be in the forefront of policymaking for quantum human resource development and to get ahead of the curve before bottlenecks emerge.

Building the Pipeline. The EU must ensure that its policies cover the entire talent pipeline, from high school to undergraduate to postgraduate, as well as the upskilling of legacy talent. Although the EU's Quantum Flagship has unveiled a plan for education, it isn't clear whether the funding involved is commensurate with the EU's goals, nor is it clear which stakeholders are responsible for overseeing implementation of the plan. Above all, business needs to be a key part of the process of creating the talent pipeline and transforming academic brainpower into engineering and business talent. There's no dearth of examples; Taiwan's semiconductor manufacturers fund PhD programs in semiconductors and recruit researchers for traineeships in order to support their upskilling.

Attracting Global Talent. The fight for quantum talent is likely to become global as it already is in other high-tech industries. The EU must therefore start offering incentives to attract quantum talent from overseas and make the continent accessible to them. For example, mainland Chinese companies have hired senior executives from Taiwanese chip-makers by offering them hefty monetary incentives; and Taiwan offers foreigners who work in priority areas, such as technology, major tax exemptions for long periods of time. The EU could fashion similar initiatives to make the region more attractive to foreigners. Quantum computing should be included in EU immigration policies to facilitate the movement of expatriates such as the fast-track French visa that has been created for foreigners working in or creating startups in the country.

The EU's current standing in the global quantum computing sweepstakes is best captured by a memorable *Dilbert* cartoon by Scott Adams. In it, the Pointy Haired Boss asks the bespectacled Wally how his quantum computing prototype is coming along, and Wally answers: "Great. The project exists in a simultaneous state of being both totally successful and not even started." In the same way, the EU has, until now, been both successful and also completely unsuccessful in quantum computing.

As BCG data and analysis show, the EU has developed some capabilities, but it hasn't translated them into major advances in quantum computing research or a vibrant private sector that rapidly and effectively develops applications, as the US and China are doing. Only by tackling head-on the three challenges on which this report has focused can the EU hope to be a contender in the quantum computing industry of the future. If it fails to respond to the challenges in time, the EU will lose the quantum computing battle and suffer a severe blow to its technological independence, its digital capabilities, and, indeed, its global competitiveness.

Appendix: Quantum Snapshots, by Country

Quantum Computing Profile: Australia

Australia

Recent and historical policies

- **2020:** Australia lists quantum as a national security concern, making foreign investments undergo an approval process
- **2020:** Launch of the Sydney Quantum Academy to catalyze the development of quantum economy with **$15 million** in government funding
- **2021:** Federal government announces plans to invest **$80 million** in Quantum Computing, including **$50 million** for the Quantum Commercialisation Hub to foster strategic partnerships
- **2021:** Australia signs an international cooperation agreement with the US on quantum computing
- **2021:** The UK, Australia, and the US sign the AUKUS trilateral security pact, which includes a commitment to cooperate on quantum capabilities
- **2022:** Australia's army holds a Quantum Technology Challenge to look for quantum solutions

Official targets

- No target

Funding estimates

- **Public:** ~**$0.1 billion** (since 2021)
- **Private deals[1]:** **$0.048 billion** (since 2010)

Public instruments

- ✅ Direct funding of R&D
- Policies supporting education
- ✅ Policies supporting international cooperation
- Export controls

Market context

- **Market size:** N/A
- **Market share:** N/A
- **Key players:** Quantum Brilliance, Quintessence Labs, Opacity, Silicon Quantum Computing

✅ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

Note: Dollar amounts are expressed in US dollars.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: Canada

Canada

Recent and historical policies

2018: Government allocates **€10 million** to the University of Waterloo's Institute for Quantum Computing

2020: Creation of the Canada Quantum Industry consortium

2021: Canada announces a **$30 million** contribution to D-Wave to support a $120-million project to develop quantum computer hardware and software systems

2021: Federal government announces **$0.28 billion** funding over seven years to build a national quantum strategy

Official targets

- No clear target, only estimates from the National Research Council that by 2030 Canada will grow an **$8.2 billion** quantum industry, employ 16,000 people, and generate **$3.5 billion** for the government

Funding estimates

- **Public:** ~**$0.3 billion** (since 2021)
- **Private deals[1]:** **$0.65 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** $301 million (2022)
- **Market share:** 12% (2022)
- **Key players:** Anyon Systems, 1QBit, Agnostiq, CEW Systems Canada Inc., D-Wave, Adaptive Finance Technologies, CogniFrame, EvolutionQ, Xanadu

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

Note: Dollar amounts are expressed in US dollars.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: China

China

Recent and historical policies

2015: Digital Skill Road specifies quantum for domestic use and export as a priority

2016: 13th five-year plan launches a project for quantum and communication, including expansion of the national quantum communications infrastructure, development of a general quantum computer prototype, and creation of a practical quantum simulator

2016: Micius quantum communication satellite is successfully launched

2020: China's Jiuzhang quantum computer achieves quantum supremacy

2021: 14th five-year plan prioritizes quantum and installation of a satellite-enabled "quantum-encrypted communications capability" by 2030

Official targets

- Install a satellite-enabled, global "quantum-encrypted communications capability" by 2030

Funding estimates

- **Public:** **~$11 billion** (since 2016)
- **Private deals[1]:** **$0.15 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** $268 million (2022)
- **Market share:** 11% (2022)
- **Key players:** CIQTEK, Origin Quantum, Qasky, QuantumCTek, QuDoor, Huawei Cloud, QuDoo Alibaba, Baidu, Tencent

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: EU

EU

Recent and historical policies

2016: Launch of Quantera, EU initiative funding quantum research programs with over **€50 million** in funding (calls in 2017, 2019 and 2021)

2018: Foundation of the large-scale research project, Quantum Flagship with **€1 billion** in funding

2019: Member states sign EuroQCI Declaration, agreeing to work together to develop a quantum communication infrastructure (EuroQCI) to be operational in 2027

2021: Commission selects a consortium of companies (e.g., Airbus, Leonardo, and Orange) to study the design of the future European quantum communication network

2022: Launch of the European Innovation Council program with **€1.7 billion** in funding for innovators to scale up and create new markets, including quality control

Official targets

- Have a first computer with quantum acceleration by 2025, paving the way for Europe to be at the cutting edge of quantum capabilities by 2030

Funding estimates

- **Public[1]:** **~$5.2 billion** (since 2014)
- **Private deals[2]:** **$0.27 billion** (since 2010)

Public instruments

- ✅ Direct funding of R&D
- ✅ Policies supporting education
- ✅ Policies supporting international cooperation
- Export controls

Market context

- **Market size[3]:** $346 million (2022)
- **Market share[3]:** 14% (2022)
- **Key players:** IQM, C12 Quantum, IBM Quantum System One, Quandela, Quantum Factory, Atos, Avanetix, Algorithmiq, Quantastica, QuantFI, Pasqal, Multiverse

✅ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Considering investments from the central EU and four key EU countries (France, Germany, the Netherlands, and Finland).

[2]Including M&A, private deals, and placements.

[3]Estimates for Europe, excluding the UK.

Quantum Computing Profile: Finland

Finland

Recent and historical policies

2020: Government grants **€20.7 million** to VTT and co-innovation partner IQM to build Finland's first quantum computer

2021: VTT and IQM announce Finland's first operational 5-qubit quantum computer

2021: Announcement of the Finnish Quantum Institute

Official targets

- No official government target
- VTT Technical Research Centre of Finland aims to create a 50-qubit system by 2024

Funding estimates

- **Public:** ~**$0.02 billion** (since 2018)
- **Private deals[1]: $0.016 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** N/A
- **Market share:** N/A
- **Key players:** IQM, Algorithmiq, Quantastica

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: France

France

Recent and historical policies

2019: Ministry of Economy implements regulations to restrict foreign investment in national quantum companies

2020: Creation of a quantum taskforce to draft a national plan with state, research, and financial sector representatives

2021: French government announces a **€1.8 billion** investment plan in quantum computing, with **€1.1 billion** from the French government, **€0.2 billion** from European funding, and **€0.55 billion** from the private sector

2022: French government announces a program to offer a national quantum platform to researchers and companies with a budget of **€170 million**

Official targets

- Become one of top three world-leading powers in quantum

Funding estimates

- **Public:** **~$1.1 billion** (since 2021)
- **Private deals[1]:** **$0.068 billion** (since 2010)

Public instruments

- ✅ Direct funding of R&D
- ✅ Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** $88 million (2022)
- **Market share:** 3% (2022)
- **Key players:** C12 Quantum, Muquans, Pasqal, Alice & Bob, Quandela, Atos, QuantFi, Qubit Pharmaceuticals, CryptoNext Security

✅ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: Germany

Germany

Recent and historical policies

- **2018:** Allocation of **€0.65 billion** in government funding for four years
- **2020:** Allocation of a **€0.30 billion** government funding on quantum
- **2021:** Germany announces its "Quantum Computing Roadmap" with **€2 billion** of investments
- **2021:** Creation of a German quantum consortium, of industry players such as BASF, BMW, Infineon, SAP, and Siemens
- **2021:** Partnership with IBM to bring a quantum computer to Fraunhofer research institute (the first IBM quantum computer outside the US)
- **2022:** Partnership with D-Wave (Canada) to bring a 5,000-qubit quantum annealing computer to Europe

Official targets

- Become a first-league player in quantum
- Create a German-made quantum computer by 2026

Funding estimates

- **Public:** ~**$3.4 billion** (since 2018)
- **Private deals[1]:** **$0.016 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** $126 million (2022)
- **Market share:** 5% (2022)
- **Key players:** Cube Robot X, Eleqtron, Infineon Technologies Ag, Keequant, Kiutra, Q.Ant, Quantum Factory, Avanetix, JoS Quantum, Quantistry, QuantumFD

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: Israel

Israel

Recent and historical policies

2019: Government allocates **$350 million** for quantum in the following 6 years

2019: Creation by the Israel Innovation Authority of a Quantum Consortium, gathering industry and academia

2021: Israel officially joins Horizon Europe, enabling it to collaborate with the EU on quantum research topics

2022: Defense Ministry and Israel Innovation Authority announce **$62 million** in funding to build Israel's first quantum computer

Official targets

- No target

Funding estimates

- **Public:** **~$0.4 billion** (since 2019)
- **Private deals[1]:** **$0.1 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** N/A
- **Market share:** N/A
- **Key players:** Quantum Machines, ClassiQ, QEDma Quantum Computing, QuantLR

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: Japan

Japan

Recent and historical policies

2019: Inclusion of quantum in a moonshot R&D national program with estimated funding for quantum of **$0.1 billion**

2020: IBM and University of Tokyo launch the Quantum Innovation Initiative Consortium to accelerate R&D

2020: Development of a government quantum roadmap with about **$270 million** allocated to it

2021: Creation of an **$875 million** R&D fund to advance tech, including quantum computing, but without making specific allocations

2022: Japan doubles quantum-related investment in its fiscal 2022 budget to **$0.7 billion**

Official targets

- Be a quantum leader by 2035
- Produce a 100-qubit machine by 2030, followed by a more powerful, full-fledged quantum computer by around 2039

Funding estimates

- **Public:** **~$1.1 billion** (since 2020)
- **Private deals[1]:** **$0.010 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** $177 million (2022)
- **Market share:** 7% (2022)
- **Key players:** Hitachi, NEC, Fujitsu and Toshiba, NTT Laboratories, A*Quantum

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: Netherlands

Netherlands

Recent and historical policies

2008-2018: Estimated that over 93 Dutch quantum projects received **€123 million** in funding for Horizon 2020

2013: Creation of QuTech (Advanced Research Center for Quantum Computing and Quantum Internet)

2015: Ministry of Economic Affairs committed to financing QuTech in a national partnership for **€135 million** over ten years

2019: Publication of a National Agenda on Quantum Technologies (Quantum Delta) with a seven-year investment of around **$700 million**

2020: Launch by a Dutch startup of Europe's first public quantum computing platform, Quantum Inspire

Official targets

- Be a leading international center and hub for quantum technology

Funding estimates

- **Public:** ~**$0.85 billion** (since 2019)
- **Private deals¹:** **$0 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

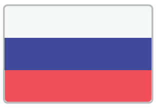
- **Market size:** N/A
- **Market share:** N/A
- **Key players:** QphoX, QuantWare,

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: Russia



Russia

Recent and historical policies

- **2019:** Launch of Russia's first prototype of a quantum computer
- **2020:** Announcement of a **$790 million** government investment in quantum
- **2021:** Development of a prototype 4-qubit ion quantum computer
- **2022:** Creation of a National Quantum Lab, grouping companies and universities with the launch of educational programs programmed

Official targets

- Creation of a common network of quantum computers in Russia
- 30- to 100-qubit quantum computer by 2024
- Additional detailed targets by tech (e.g., number of qubits in a neutral atom computer)

Funding estimates

- **Public:** **~$0.8 billion** (since 2020)
- **Private deals[1]: $0 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- ✓ Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** N/A
- **Market share:** N/A
- **Key players:** Rostech, Rosatom, RzhD

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: Switzerland

Switzerland

Recent and historical policies

2019: ETH creates the first worldwide master of Quantum Engineering

2019: IBM partners with ETH and EPFL for quantum research

2021: CERN unveils its roadmap with medium- and long-term research milestones

2021: ETH is investing 32 million Swiss francs to build a Quantum Computing Hub

2021: Switzerland has access limited to Horizon Europe for R&D funding, including for quantum

Official targets

- No target

Funding estimates

- **Public:** N/A
- **Private deals[1]:** 0

Public instruments

- Direct funding of R&D
- ✓ Policies supporting education
- Policies supporting international cooperation
- Export controls

Market context

- **Market size:** N/A
- **Market share:** N/A
- **Key players:** Qnami, Zurich Instruments, Miraex, Terra Quantum, ID Quantique, Synergy Quantum

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: UK

UK

Recent and historical policies

- **2013:** Creation of the National Quantum Technologies Programme, to support R&D and tech transfer to marketplace
- **2019:** Second phase of the NQTP, with a revision of research agendas and creation of an UK Industrial Challenge fund with **$27 million** to foster production of prototype devices
- **2020:** Launch of the National Quantum Computing Centre, an R&D center
- **2021:** UK signs cooperation agreements with US
- **2021:** Launch of a new **$260 million** AI and QC center in partnership with IBM
- **2021:** The UK, Australia, and the US sign the AUKUS trilateral security pact, which includes a commitment to cooperate on quantum capabilities
- **2022:** Implementation of restriction of foreign investment in quantum UK companies
- **2022:** Announcements that a UK National Quantum Strategy will be published this year

Official targets

- "Go big on quantum computing," building a general-purpose quantum computer
- Secure 50% of the global quantum market by 2040

Funding estimates

- **Public: ~$1.8 billion** (since 2014)
- **Private deals[1]: $0.2 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- ✓ Policies supporting education
- ✓ Policies supporting international cooperation
- Export controls

Market context

- **Market size:** $160 million (2022)
- **Market share:** 16% (2022)
- **Key players:** Oxford Quantum Circuits, Universal Quantum, Riverlane, PhaseCraft, Cambridge Quantum, Rahko, Quantum Motion, PhaseCraft, QLM, Crypto Quantique, Crypta Labs, ORCA Computing, Quantinuum

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

Quantum Computing Profile: US

US

Recent and historical policies

2019: The National Quantum Initiative Act creates a national plan for quantum computing and provides a framework to coordinate work from different agencies

2019: US signs cooperation agreements with Japan

2020: Creation of the national Q-12 educational partnership, focused on fostering training and a quantum learning environment with industrial partners such as IBM

2021: The UK, Australia, and the US sign the AUKUS trilateral security pact, which includes a commitment to cooperate on quantum capabilities

2021: Federal government increases annual budget for quantum computing to **$0.7 billion**

2021: US introduces export controls on Chinese quantum companies

Official targets

- No clear target, but to be a world leader not relying on other countries

Funding estimates

- **Public:** ~**$3 billion** from federal governmentand specific agencies (since 2019)
- **Private deals[1]:** **$1.8 billion** (since 2010)

Public instruments

- ✓ Direct funding of R&D
- ✓ Policies supporting education
- ✓ Policies supporting international cooperation
- ✓ Export controls

Market context

- **Market size:** $679 million (2022)
- **Market share:** 27% (2022)
- **Key players:** IBM, Intel, Rigetti, Google, Atom Computing, Coldquanta, Azure Quantum, Qcware, Coldquanta, Strangeworks

✓ = the country meets the criterion listed

Sources: Literature research; AMR quantum data (2017); BCG analysis.

[1]Including M&A, private deals, and placements.

About the Authors

François Candelon is a managing director and senior partner in the Paris office of Boston Consulting Group, and a global director of the BCG Henderson Institute. You may contact him by email at candelon.francois@bcg.com.

Jean-François Bobier is a partner and director in the firm's Paris office, and the leader of its R&D initiative on quantum computing and technology and digital organization. You may contact him by email at bobier.jean-francois@bcg.com.

Maxime Courtaux is a project leader in BCG's Paris office, and a BCG Henderson Institute ambassador. You may contact him by email at courtaux.maxime@bcg.com.

Gabriel Nahas is a senior data scientist in the firm's São Paulo office and a BCG Henderson Institute ambassador. You may contact him by email at nahas.gabriel@bcg.com.

For Further Contact

If you would like to discuss this report, please contact the authors.

BCG

BCG HENDERSON INSTITUTE

THE RACE TO THE QUANTUM FUTURE THAT EUROPE CAN'T AFFORD TO LOSE

BOSTON CONSULTING GROUP | BHI