ECIPE | EUROPEAN CENTRE FOR INTERNATIONAL POLITICAL ECONOMY

POLICY BRIEF – No. 03/2025

Quantum Technology: A Policy Primer for EU Policymakers

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Thanks to **Bianca Donati** *and* **Jules Borgetto** *for research support.*

EXECUTIVE SUMMARY

Quantum technology is rapidly emerging as a transformative force with the potential to reshape industries ranging from finance and pharmaceuticals to automotive and aerospace. In 2024 alone, investments in quantum technology reached over USD 56 billion. Its development, however, presents unique geopolitical challenges, stemming from its applications in defence and encryption, as well as its power to unsettle established comparative advantages and market specialisations across countries.

Against this backdrop, an open and collaborative approach to quantum innovation is critical for maximising the benefits of this technology. Countries perform more effectively in quantum technology when they support cross-border collaborations and market specialisation. Firms producing quantum hardware or software solutions can sell to a range of industrial users who, in turn, integrate these cutting-edge systems into goods and services. Such synergy reduces the overall risks and costs of R&D, as different partners share both the financial burden and any uncertainties related to the commercial viability of quantum applications.

Moreover, collaboration fosters a wider diffusion of quantum technologies. As firms specialising in quantum computing, communication, or sensing deepen their expertise, their insights permeate adjacent sectors through the shared knowledge enabled by joint collaborations. Conversely, restrictive policies that limit interaction between domestic and foreign firms risk stifling innovation. Self-reliance strategies reduce opportunities for knowledge-sharing, limit the pool of potential partners, and ultimately slow the pace of quantum breakthroughs.

This operating framework supports the current EU approach to quantum technology, which emphasises openness and encourages a higher number of collaborations between EU and non-EU companies. This approach is grounded in economic realities: the EU ranks second only to the US in terms of the number of companies and collaborations between firms and it thrives on partnering with non-EU countries as the number of collaborations with companies outside the EU far exceeds the number of collaborations within the EU.

To develop quantum technologies, the EU should double down on openness and follow three key principles:

1. **Interdependency is a strength not a weakness:** it enables mutually beneficial cross-border collaborations that drive innovation, mitigate R&D risks, generate positive spillover effects across industries, and create symbiotic relationships to the benefit of producers and users of quantum technology.
2. **You cannot do everything yourself:** specialisation is essential for innovation in quantum technologies while attempts of self-reliance are impractical and counterproductive.
3. **Establish an open R&D strategy:** set up public-private partnerships and inclusive funding for international collaborations in order to accelerate the development and diffusion of quantum technologies.

1. INTRODUCTION

Quantum technology is developing rapidly. In 2022, global public and private investments in quantum technology were estimated to have reached USD 35.5 billion[1], and, based on our calculations, in just two years, these investments have increased by a whopping 60 percent, reaching over USD 56 billion in 2024. Moreover, it is highly likely that this spending will continue to accelerate in the future.

This growing interest is driven by the commercial and scientific opportunities offered by quantum technology. Each breakthrough in this technology drives advancements in three critical areas: computing, communications, and sensing. In turn, innovations in these areas have the potential to address challenges across aerospace, automotive, pharmaceuticals, energy, or finance.

However, like any transformative technology with the potential to reshape the global economy, quantum technology has become enmeshed in the language of geopolitics. Several nations have set ambitious targets to achieve "quantum autonomy" or "quantum sovereignty," and some even aspire to attain "quantum supremacy." These policies have created a sense that countries operate in a geopolitical race, where nations vie for dominance at the forefront of quantum advancements.

True, given its applications in defence and encryption, it is inevitable that geopolitics will play a role in the development of quantum technologies. However, a protectionist or "my-country-first" approach would be counterproductive. Quantum is an emerging field of knowledge and experimentation, and no single country possesses the resources to lead across all areas of expertise. Instead, nations must rely on deep cooperation and coordination, particularly among allied countries.

Therefore, to maintain the steady pace of quantum developments, it is important to prioritise research partnerships between academic institutions, industry leaders, and governments as means for accelerating progress in quantum technologies and bringing new applications closer to commercialisation. The most critical factor in the development of these partnerships is each country's position within the emerging supply chains of quantum technologies. For that reason, a country's relevance should not be assessed based on its "autonomy" but rather on its ability to contribute to and connect with the development of quantum technologies in other nations. In essence, a country's importance lies in its value to others, not itself.

The EU is well positioned to play a significant role in the development of quantum technology, thanks to its combined efforts across member states. It has a strong foundation, with both national and European public R&D programmes supporting research in quantum technologies; a mix of new and established companies developing quantum applications; a robust industrial

[1] World Economic Forum. (2022, September). State of Quantum Computing: Building a Quantum Economy. Available at: https://www3.weforum.org/docs/WEF_State_of_Quantum_Computing_2022.pdf

base ready to adopt these innovations; and a university system producing more STEM graduates than the United States[2].

This is the first paper in a series of studies exploring the political and economic dimensions of quantum technology. It serves as a primer and guide to developments in the field, tailored for policymakers, academics, and technology observers. Chapter two provides an overview of quantum technology, introducing its fundamental concepts and exploring the applicability of quantum technologies in computing, communication, and sensing. Chapter three presents a series of figures positioning EU private companies working on quantum technology within a web of cross-country partnerships and collaborations. The primer concludes with a set of principles for EU policymakers designed to foster the development of quantum technologies in the EU.

2. BASIC CONCEPTS AND APPLICATIONS OF QUANTUM TECHNOLOGY

Quantum technology may, figuratively, be "rocket science", but the basic components of this development can be grasped without an advanced science degree. Quantum technologies can be categorised as functionalities as well as tools that are based on applied quantum theory. They include hardware and software that leverage the core principles of quantum mechanics, including superposition (where particles can exist in multiple states simultaneously) and entanglement (where particles become interconnected in ways that classical physics cannot explain). See Annex I for a full description of basic concept used in quantum.

Key developments and applications in quantum technology are presented in three main areas: quantum computing; quantum communication; and quantum sensing.

2.1 QUANTUM COMPUTING

Quantum computing leverages the principles of quantum physics to process information in ways that classical computers cannot. It challenges the traditional notion of information transfer, where information is transmitted using bits (0s and 1s). Instead, quantum computers use quantum bits, or qubits, which can exist in multiple states simultaneously due to the quantum property of superposition.

The result are chips which can compute a problem significantly faster than a classical computer. In 2019, Google, in collaboration with NASA and Oak Ridge National Laboratory, revealed the Sycamore chip, a processor with 54 quantum qubits, capable of performing a series of tasks in 200 seconds while a traditional computer would require 10,000 years.[3] More recently, in December 2024, Google's unveiled Willow, a quantum chip, which in less than five minutes, was

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[2] OECD. Number of graduates with bachelor's or equivalent level in science, technology, engineering (including ICT fields), and mathematics (STEM). In 2021, there were 523,763 new tertiary graduates in STEM in the EU25 (Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, and Sweden) compared to 490,334 in the US.

[3] Arute, F., Arya, K., Babbush, R., Bacon, D., Bardin, J. C., Barends, R., & Martinis, J. M. (2019). Quantum supremacy using a programmable superconducting processor. Nature, 574(7779), 505-510.

capable of completing computations that would take the fastest supercomputers approximately 10 septillion (10^{25}) years.[4]

Quantum computing also has the potential to enhance existing technologies. For example, combining quantum computing with machine learning (ML) techniques and algorithms can lead to substantial improvements in supervised, unsupervised, and reinforcement learning. Similarly, quantum computing can be used to solve optimisation problems[5] and run simulations[6] faster and more efficiently than classical methods. Some of these developments, which can be applied in multiple sectors[7], are identified in Table 1.

TABLE 1: QUANTUM COMPUTING APPLICATIONS

Sector	Application	Industry Examples
Aerospace	Simulation of high-fidelity designs with improved aerodynamic properties, increased speed, and optimisation	Airbus (France) and IonQ announced a collaboration in 2022 for exploring the potential application of quantum computing for aerospace services in the development of a prototype aircraft-loading quantum application.[8]
Automotive	Vehicle routing and route optimisation	Classiq (Israel), Nvidia (US) and BMW Group (Germany) announced a collaboration to optimise mechatronic systems (a field that integrates mechanical engineering, electronics, and computer science and control systems) for automotive.[9]
Energy	Enabling energy distribution and storage	PsiQuantum (US) and Mitsubishi UFJ Financial Group (Japan) announced a collaboration to simulate excited states of photochromic molecules to develop efficient energy storage.[10]
Finance	Experimental approaches in fraud detections, portfolio optimisation and accuracy in credit decision algorithms.	Quantum Motion (UK) and Goldman Sachs (US) in a partnership, developed a quantum algorithm for improving option pricing in financial services.[11]
Pharmaceutical	Accelerate drug discovery process and development.	Japan Tobacco Inc. (Japan) and D-wave (Canada) announced a collaboration to leverage quantum computing and AI in drug discovery process and expanding the space for pharmaceutical small compounds.[12]

[4] Neven, H. (2024, December 9). Meet Willow, our state-of-the-art quantum chip. Google. Available at: https://blog.google/technology/research/google-willow-quantum-chip/

[5] For instance, Quantum optimisation has the potential to enhance weight management in port and freight operations, enabling more efficient and precise handling of cargo logistics. Source: D-wave. Quantum Optimization. Available at: https://www.dwavesys.com/solutions-and-products/quantum-optimization/quantum-optimization-landing-page/

[6] For instance, Quantum simulators can aid in the development of high-temperature superconductors, enabling the transmission of power with zero energy loss. Source: D-wave. Quantum Optimization. Available at: https://www.dwavesys.com/solutions-and-products/quantum-optimization/quantum-optimization-landing-page/

[7] Among others, quantum computing is anticipated to have transformative impacts across various fields, including chemistry, biology, physics, finance, meteorology, and geology.

[8] IonQ. (2022, August 18). IonQ, Airbus Sign Agreement to Collaborate on Aircraft Loading Project using Quantum Computing. Available at: https://ionq.com/news/august-18-2022-ionq-2022-airbus

[9] Classiq. (2024, June 20). Classiq Collaborates with BMW Group and NVIDIA to Drive Quantum Computing Applicability in Electrical Systems Engineering. Available at: https://www.classiq.io/insights/classiq-collaborates-with-bmw-and-nvidia

[10] PsiQuantum. (2024, May 29). PsiQuantum, Mitsubishi UFJ Financial Group and Mitsubishi Chemical announce partnership to design energy-efficient materials on PsiQuantum's fault-tolerant quantum computer. Available at: https://www.psiquantum.com/news-import/psiquantum-mitsubishi-ufj-financial-group-and-mitsubishi-chemical-announce-partnership-to-design-energy-efficient-materials-on-psiquantums-fault-tolerant-quantum-computer

[11] Quantum Zeitgeist. (2024, November 2). Goldman Sachs Partners with Quantum Motion on Finance Applications. Available at: https://quantumzeitgeist.com/goldman-sachs-partners-with-quantum-motion-on-finance-applications/#google_vignette

[12] D-Wave. (2024, October 1). Japan Tobacco Inc. and D-Wave Announce Collaboration Aimed at Accelerating Innovative Drug Discovery with Quantum AI. Available at: https://www.dwavesys.com/company/newsroom/press-release/japan-tobacco-inc-and-d-wave-announce-collaboration-aimed-at-accelerating-innovative-drug-discovery-with-quantum-ai/

2.2 QUANTUM COMMUNICATION

Quantum communication bridges the fields of optical communications and quantum physics. It uses similar hardware and wavelengths to optical systems, typically operating in the visible or near-visible spectrum. However, unlike traditional systems that modulate entire laser beams, quantum communication manipulates individual photons. This approach leverages the quantum properties of photons, such as superposition and entanglement to establish safe communication channels.

Security is one of the primary advantages of quantum communications. Superposition and entanglement in combination with the no-cloning theorem,[13] makes quantum communications virtually unhackable. Any attempt to intercept or measure qubits would cause their quantum state to collapse, leaving clear evidence of tampering. Many companies have leveraged this advantage to create networks for transmitting highly sensitive data through a process called quantum key distribution (QKD). QKD transmits encrypted data as classical bits over networks, while the keys required for decryption are encoded and transmitted in a quantum state using qubits.

There are several examples of quantum communications that have been applied over the past few years. In 2017, China established a 2,032-kilometer ground link between Beijing and Shanghai, demonstrating the usage of QKD over fiber optic cables and satellite relays. Two years later, in 2019, a start-up company in the US, Quantum Xchange set up an 800 km fiber-optic cable along the East Coast to create a QKD network from Boston to Washington DC[14]. In 2020, researchers from Nanjing University in China announced the development of drones equipped with quantum communications technology. These drones were used to generate pairs of entangled light particles to transmit information in quantum states[15].

Similar to quantum computing, quantum communication holds several promising applications in different sectors. Some of these developments have been identified in Table 2.

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[13] The no-cloning theorem in quantum mechanics asserts that quantum operations are unitary linear transformations of quantum states, making it fundamentally impossible to perfectly replicate arbitrary and unknown quantum states. Wootters, W. K., & Zurek, W. H. (1982). A single quantum cannot be cloned. Nature, 299(5886), 802-803; see: Dieks, D. G. B. J. (1982). Communication by EPR devices. Physics Letters A, 92(6), 271-272.

[14] Giles, M. (2019, February 14) Explainer: What is quantum communication? MIT Technology Review. Available at: https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/#:~:text=Explainer%3A%20What%20is%20quantum%20communication%3F

[15] Chen, S. (2020, January 10) China is developing drones that use quantum physics to send unhackable messages. South China Morning Post. Available at: https://www.scmp.com/news/china/science/article/3045229/china-developing-drones-use-quantum-physics-send-unhackable

TABLE 2: QUANTUM COMMUNICATIONS APPLICATIONS

Sector	Application	Example
Aerospace	Securing data transmission and introducing high bandwidth communications.	Boeing (US) and HRL Laboratories (US) in a collaboration have used quantum networks to go beyond simple point-to-point communication.[16]
Banking	Protecting exchange of cryptographic keys to address cybersecurity threats, and protecting consumer data.	The Monetary Authority of Singapore (MAS) announced a collaboration with HSBC (Hong Kong, Shanghai), and SPTEL and SpeQtral (Singapaore) to study QKD solutions in banking sector.[17]
Finance	Securing messaging in transactions banks, merchants, customers, and government. agencies; credit card authorisations; wire transfers; account information; and other types of communications through post quantum cryptography and quantum key distribution.	Toshiba Digital (Japan) and KT Corporation (South Korea) in a partnership have demonstrated the use of hybrid quantum secure communications to secure communications at Shinhan Bank (South Korea) through a network that connects the bank's Seoul headquarters with its Gangnam facilities, a distance of about 22 kilometres.[18]

2.3 QUANTUM SENSING

Quantum sensing refers to the application of quantum physics to enhance the performance of various sensors, such as clocks, accelerometers, gravimeters, antennas, electromagnetic radiation detectors, and sensors for steady electric or magnetic fields. Unlike quantum computing and communications, quantum sensing typically does not introduce entirely new capabilities, but in some cases, the scale of improvement can be significant enough to enable new applications.

The measurement values provided by conventional sensors change gradually over time, making it difficult to reduce measurement variation and error. In contrast, quantum sensing offers significant improvements in the accuracy and efficiency of measurements.[19] These improvements are achieved through quantum sensing's ability to detect changes in motion, electric fields, and magnetic fields. Quantum sensors can be used for intelligence, surveillance purposes, and reconnaissance, such as the use of Rydberg atoms[20] for highly sensitive antennas[21]. Other promising applications of quantum sensing are outlined in Table 3.

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16 Boeing. (2024, September 10). Boeing Pioneering Quantum Communications Technology with In-Space Test Satellite. Available at: https://investors.boeing.com/investors/news/press-release-details/2024/Boeing-Pioneering-Quantum-Communications-Technology-with-In-Space-Test-Satellite/default.aspx

17 Monetary Authority of Singapore. (2024, August 14). MAS Collaborates with Banks and Technology Partners on Quantum Security. Available at: https://www.mas.gov.sg/news/media-releases/2024/mas-collaborates-with-banks-and-technology-partners-on-quantum-security#:~:text=The%20Monetary%20Authority%20of%20Singapore,(QKD)%20in%20financial%20services.

18 Toshiba. (2024, April 19). Toshiba Digital Solutions and KT Demonstrate Hybrid Quantum Secure Communications with South Korea's Shinhan Bank. Available at: https://www.global.toshiba/ww/news/digitalsolution/2024/04/news-20240419-01.html

19 Soller, D. (2024a). "Advanced sensor technology." Quantum Sensing Insights. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/tech-forward/quantum-sensing-poised-to-realize-immense-potential-in-many-sectors

20 Rydberg atoms are atoms in highly excited states, distinguished by one or more electrons occupying orbitals with high principal quantum numbers (n), typically exceeding 10. This unique state gives rise to exaggerated properties, such as heightened sensitivity to external electric and electromagnetic fields, making them highly useful for a range of applications in quantum technologies. See: Gallagher, T. F. (1988). Rydberg atoms. Reports on Progress in Physics, 51(2), 143.

21 Defense Science Board, 2019

TABLE 3: QUANTUM SENSING APPLICATIONS

Sector	Application	Example
Navigation (Aerospace)	Accuracy in positioning GPS in unreliable environments and securing navigation.	Airbus (France) and Bosch Quantum Sensing (Germany) in a collaboration are developing aircraft navigation systems that enable the acquisition of data for safe flight.[22]
Medicine	Advancing neuroscience applications and high-speed imaging and high sensitivity and spatial resolution.	Cambridge Consultants (UK) and Qnami (Switzerland) in a partnership are working to identify where and how NV magnetometry can offer application in biomedical area.[23]
Geology and national resources and meteorology	Discovery of new mineral and water resources (oil and gas prospecting, mining). Precision research and redefining standards and units.	Q-CTRL (Australia) and United States Geological Survey (USGS) have entered in a Cooperative Research and Development Agreement (CRADA) to investigate quantum sensing for geological sciences for identifying hazard detection and enhanced monitoring.[24]

3. POLICY PRINCIPLES FOR THE DEVELOPMENT OF QUANTUM TECHNOLOGY IN EUROPE

In order to sustain current activities and new ones that will push the knowledge frontier of quantum technology further, governments, firms, and academic institutions must continue investing in R&D activities. However, no single country has the array of knowledge, goods and services necessary to deploy quantum technologies in isolation. Therefore, given the specialised expertise required to work in quantum technology, these partnerships must involve cross-border collaboration.

This points to the degree of dependence between different companies, not only the ones involved in quantum, but also companies that want to leverage quantum technologies for applications in the wider economy. Some quantum technology firms focus primarily on pushing the boundaries of what quantum can achieve, while other technology firms concentrate on the deployment of products and processes which includes integrating quantum technologies into existing systems.

To explore the multilateral nature of quantum technology, this Policy Brief presents a dataset of 1,053 quantum technology collaborations involving 1,526 companies. These collaborations were collected from websites specialising in quantum-related news (e.g., The Quantum Insider, Quantum Zeitgeist) and company press releases. A collaboration between two companies is recorded if it has already commenced or has been announced. The sample focuses on industry-to-industry collaborations and covers the period from 2018 to 2024.

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[22] Bosch. Airplane navigation and Exploration of Minerals. Available at: https://www.bosch-quantumsensing.com/application-fields/navigation-and-exploration/

[23] Cambridge Consultants. (2023, January 24). Quantum sensing technology for the life sciences. Available at: https://www.cambridgeconsultants.com/quantum-sensing-for-the-life-sciences/

[24] Q-CTRL. (2024, January 16). Q-CTRL Partners with USGS to Pioneer Quantum Sensing and Computing Applications. Available at: https://q-ctrl.com/blog/q-ctrl-partners-with-usgs-to-pioneer-quantum-sensing-and-computing-applications#:~:text=Q%2DCTRL%20Partners%20with%20USGS%20to%20Pioneer%20Quantum%20Sensing%20and%20Computing%20Applications,-January%2016%2C%202024&text=Agreement%20with%20U.S.%20Geological%20Survey,resources%2C%20geologic%20hazards%20and%20ecosystems.

The dataset of collaborations and the methodology used to analyse them present three main limitations. Firstly, as the aim is to examine collaborations within the private sector, partnerships between academic or public research institutions and companies are excluded. Such collaborations are significant drivers of knowledge transfer between countries. However, the dataset does include private companies that are spin-offs of universities and public research centres. Secondly, collaborations will continue to evolve, and there is no reason to assume that past patterns will persist in the future. Therefore, the analysis should be viewed as a snapshot at a specific point in time of an ongoing process. Thirdly, the network analysis[25] used to map the collaborations provides information on the number of collaborations but does not account for their depth. In other words, two collaborations with different levels of investment are given equal weight, whereas in reality, projects with larger funding are likely to be more significant.

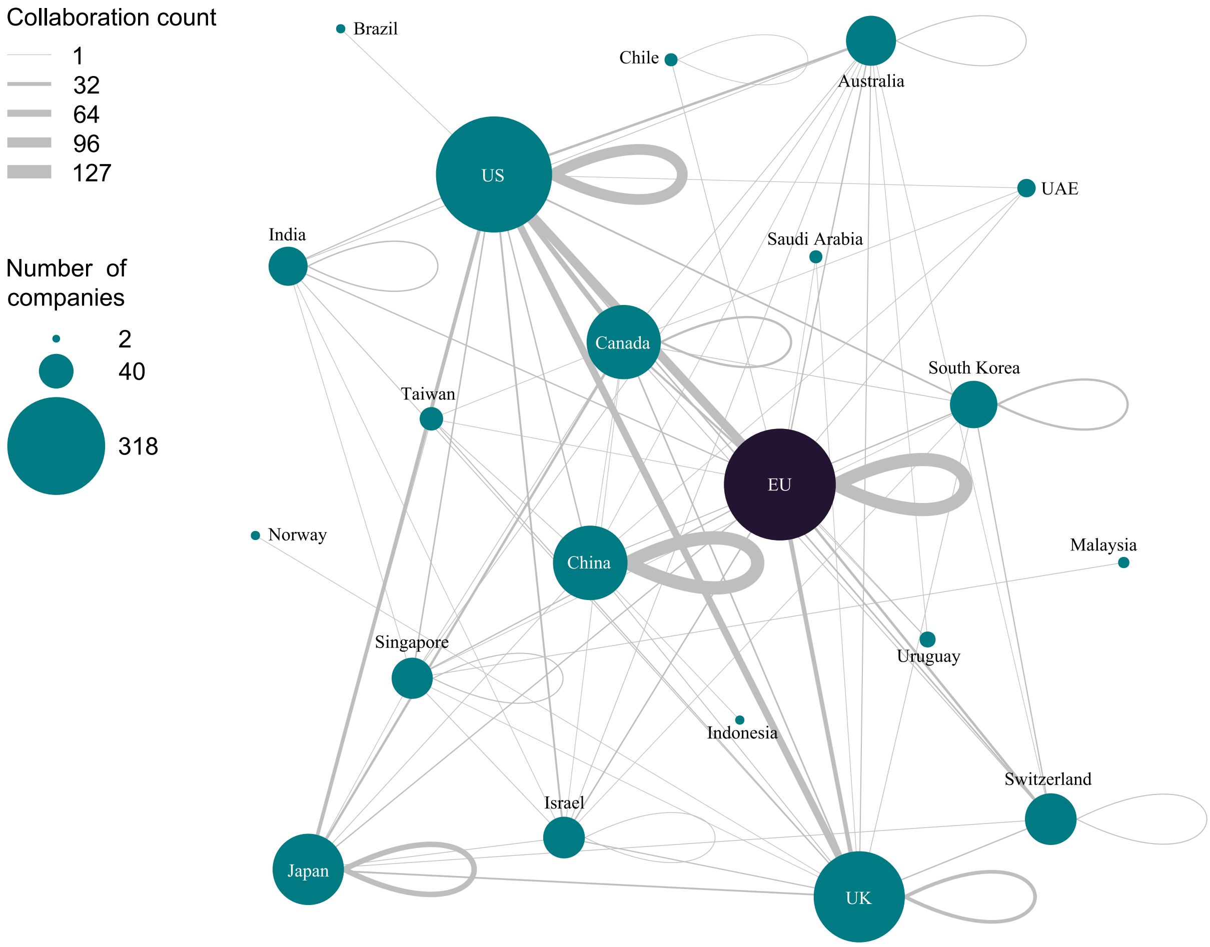
Figures 1 and 2 present the collaborations gathered in the dataset. Each line connecting two nodes represents a collaboration, such as a joint venture, between companies. Importantly, the lasso connecting a country to itself shows collaboration among companies from the same country. The figures describe two important sets of information. On one hand, the thickness of each line indicates the frequency of cross-border partnerships; thicker lines represent larger number of collaborations. On the other hand, the size of the nodes represents the number of distinct companies active in quantum technology collaborations.

Figure 1 shows that the US and the EU are central contributors to the development of quantum technology. Both regions hold central positions in the network, collectively accounting for a significant portion of all the recorded collaborations – the US represents 29 percent of all the partnerships, while the EU accounts for 20 percent – and companies – the US has 318 companies followed by the EU with 295. Moreover, the two regions are also each other's most important partners, with 84 private company collaborations.

In terms of diversity of partnerships, the EU collaborates with 16 countries, closely followed by the US with 15 partners. This diversity is a key feature of how EU and US companies approach the development of quantum technology. In contrast, China's profile of quantum collaborations is more inward looking: 84 percent of its collaborations happen exclusively among Chinese companies, as shown by the thick lasso connecting the country with itself. This is much higher than the percentage of intra-EU and intra-US collaborations which are equal to 37 and 25 percent of their respectively collaborations.

[25] The network visualisation employs the graphopt layout algorithm.

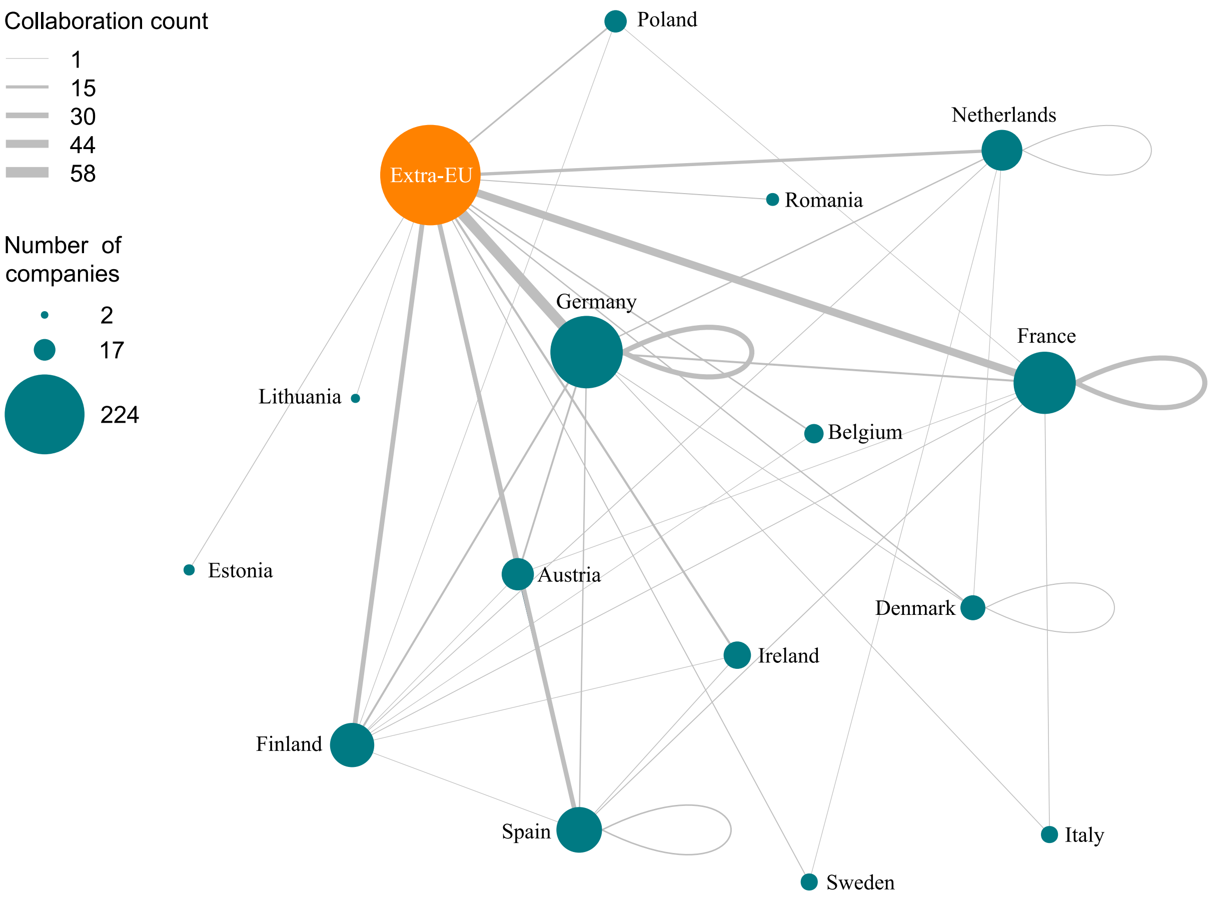
FIGURE 1: NETWORK OF QUANTUM TECHNOLOGY COLLABORATIONS



Source: Authors' calculations based on ECIPE research.

Figure 2 reproduces the same network but focusing on intra-EU linkages. The red node represents all the collaborations with countries outside of the EU (Extra-EU). An important takeaway mentioned earlier and which is clearly visible in Figure 2 is the relevance of EU partnerships between EU and non-EU companies. The number of intra-EU linkages (125) is significantly smaller than the number of collaborations between companies based in the EU and non-EU countries (213). This is clearly the case for the EU countries with the higher number of companies active in quantum technologies: Germany and France. German and French companies present 38 and 18 collaborations with companies from other EU member states, respectively. In comparison, German companies record 58 extra-EU quantum collaborations while French companies register 42.

FIGURE 2: NETWORK OF QUANTUM TECHNOLOGY COLLABORATIONS IN THE EU



Source: Authors' calculations based on ECIPE research.

Figures 1 and 2 highlight several insights. Collaborations are crucial for the development of complex technologies, such as quantum. On the one hand, they allow firms to tap into foreign expertise: each hardware component or software service contributing to quantum technology, regardless of its country of origin, is both valuable and unique. On the other hand, these collaborations demonstrate that a company has proven expertise in quantum technology. This expertise serves as a proxy for leadership, an indicator of success and of the current or potential company rewards, which will enable further investments. This is encouraging news for the EU, which records the second highest number of collaborations, only after the US.

Moreover, these collaborations support a richer and more vibrant ecosystem of companies both producing and using quantum technology. A collaboration between a developer of quantum technology and another company with the capacity to deploy that technology into products and services encourages a level of specialisation that accelerates the creation and deployment of quantum technology. For the developer, a collaboration allows them to spread the risks and costs of R&D in quantum investments, increasing potential profitability. For users, it provides a new technology without requiring them to make the R&D investments to develop it.

These collaborations will enable countries to maintain their comparative advantage and discover new ones. Radical new technologies with broad applications, such as quantum, are the driving force behind sectoral competitiveness. For instance, a country leading in financial services or pharmaceuticals can acquire quantum expertise from another country to maintain its competitive edge. Again, this is encouraging news for the EU, as 63 percent of all collaborations by EU companies are with companies located outside the EU. In contrast, the vast majority of collaborations in China occur between Chinese companies. This is because the Chinese approach to developing quantum technology is less open, with explicit government preference for domestic collaborations. Such an approach limits the pool of potential collaborations for Chinese companies producing and using quantum technologies, hindering market specialisation, profitability, and quantum technology diffusion.

Based on these three insights, we propose three key principles for the development of quantum technology in the EU:

1. Interdependency is a strength not a weakness

Interdependency is a fundamental prerequisite for quantum technology development, as it enables companies to leverage foreign expertise in mutually beneficial ways. These cross-border collaborations are essential not only for advancing quantum technology but also as a key indicator of leadership in the field. Countries with a higher number of collaborations, especially involving a diverse range of partners, demonstrate unique and highly valuable capabilities that set them apart.

These collaborations also allow companies working at the forefront of quantum technology development to mitigate risks and share the costs of R&D in quantum investments across a larger network of users. Eventually, this empowers companies developing quantum technologies to increase their investments in R&D, pushing the knowledge frontier even further.

Interdependency also generates positive spillover effects across various fields (e.g., quantum computing, communication, and sensing) and sectors such as aerospace, automotive, energy, finance, and pharmaceuticals. For example, the partnership between D-Wave, a Canadian quantum technology developer, and Volkswagen (VW), a German car manufacturer, resulted not only in the commercialisation of traffic management software but also in the development of quantum-based solutions for optimising car production logistics[26].

This is a clear example of how collaborations between companies generating quantum technologies and those using these technologies produce a symbiotic business relationship. Not only does the company developing quantum technology benefit from selling it – which enables further investments in R&D, as explained earlier – but the company purchasing this technology receives a competitiveness boost that sets it apart.

[26] D-Wave. (2021). How Volkswagen is using practical quantum computing to explore traffic optimization and more: A case story. Available at: https://www.dwavesys.com/media/2pojgtcx/dwave_vw_case_story_v2f.pdf

2. You cannot do everything yourself!

To establish a national ecosystem for quantum innovation, it is critical to identify a country's existing strengths in quantum technology and capitalise on these comparative advantages. The value chain of quantum technology is still evolving, with specialised firms spread across the world. Attempting to replicate this value chain to achieve objectives of self-reliance or national security would be not only technically impractical but also counterproductive, as quantum technology develops at a pace that requires firm specialisation.

That specialisation can be seen in the total number of collaborations. A higher number of collaborations indicates that a country is performing relatively better at producing quantum technology and diffusing it across its economy. In turn, this market specialisation supports companies in focusing on the production of quantum technologies, while other companies can concentrate their resources on deploying quantum technologies in goods and services. The overall effect of this market specialisation is faster development and broader diffusion of quantum technologies to the benefit of society at large.

In contrast, countries that follow policies or regulations that restrict the ability of the private sector to collaborate with other private companies working on quantum technology hinder the efforts of their companies developing quantum technologies and the ability of their economies to adopt these new technologies.

3. Establish an open R&D strategy

EU governments should actively address the investment gap necessary for the development and commercialisation of quantum technology by promoting public-private partnerships. These collaborations can leverage the expertise of public research institutions and universities alongside with private sector innovation.

An open approach to public R&D in quantum technologies allows R&D-intensive companies to increase the number of collaborations. In turn, a higher number of collaborations lead to the benefits mentioned before: lowers the inherent risks associated with investments in quantum applications; enables market specialisation, which supports a larger ecosystem of companies producing quantum technologies; and encourages the diffusion of these new technologies across various sectors.

Therefore, given the relevance of cross-country collaborations and the positive spillovers they generate for national companies, EU governments should consider funding non-EU companies in their public R&D funding programmes. This practice is already evident. The German subsidiary of the UK Company Universal Quantum, a spin-off from the University of Sussex, received €67 million from the German government's Aerospace Centre (DLR) to develop a single-chip quantum computer[27]. Similarly, earlier this year, the Australian government announced an investment of $617 million in PsiQuantum, a US company[28].

[27] Ingall, A.(2022, November 2). German government tasks Sussex spin-out with building a powerful quantum computer in €67M contract. University of Sussex Broadcast: News Item. Available at: https://www.sussex.ac.uk/broadcast/read/59206

[28] Quantum Insider. (April 29, 2024). PsiQuantum Receives $940 Million (AUD) From Australian Government — May Now Be World's Highest Funded Independent Quantum Firm. Available at: https://thequantuminsider.com/2024/04/29/psiquantum-receives-940-million-aud-from-australian-government/

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ANNEX I: BASIC CONCEPTS OF QUANTUM TECHNOLOGIES

Quantum bits or qubits: the basic units of quantum information and serve as a quantum version of classical binary bits. Qubits utilise the phenomenon of superposition for allowing them to exist simultaneously in a linear combination of two states: 0 and 1, or any proportion of both. This unique property enables qubits to process information in ways that classical computers cannot, resulting in an exponential boost in computational power.[29] The types of Qubits include: Superconducting Qubits, Trapped Ion Qubits, Spin Qubits, Photonic Qubits and Topological Qubits

Quantum interference: a phenomenon that occurs when two or more quantum states overlap and combine which can affect the probabilities of various outcomes during measurement. This interference becomes the basis of quantum algorithms and will lead to speed-ups in computation.[30]

Quantum Superposition: a state where qubits can exist in multiple forms simultaneously. This property significantly enhances a computer's power by allowing it to calculate with more possible states at once.[31]

Quantum Entanglement: a phenomenon where two or more qubits become interconnected in a way that the state of one qubit is dependent on the state of the other, regardless of the distance between them. This entanglement enables the instantaneous correlations between entangled particles which can be used to create and secure communication systems, and also allow the transfer of quantum states between distant qubits without physically moving the particles.[32]

Quantum Key Distribution (QKD): a secure communication method that uses quantum physics to allow two parties to create and share an encryption key for encrypting and decrypting messages. QKD functions by the transmission of light particles over fiber optic cables between parties.[33]

Quantum network: utilises quantum properties of light particles for encoding information. These processes rely on quantum phenomena such as superposition and entanglement.[34]

Quantum coherence: a property of quantum systems that allows them to maintain a stable phase relationship between different quantum states over time. This stability is crucial for the functioning of quantum technologies, including quantum computing and quantum communication.[35]

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