European Commission

Joint Research Centre

Future Directions for Quantum Technology in Europe

An analysis of policy questions

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EU Science Hub
https://joint-research-centre.ec.europa.eu/projects-and-activities/quantum-technologies_en

JRC141050

EUR 40463

Print	ISBN 978-92-68-32281-9	ISSN 1018-5593	doi: 10.2760/0209304	KJ-01-25-487-EN-C
PDF	ISBN 978-92-68-31970-3	ISSN 1831-9424	doi: 10.2760/0891087	KJ-01-25-487-EN-N

Luxembourg: Publications Office of the European Union, 2025

How to cite this report: Lewis, A. M., Scudo, P., Cerutti, I., Travagnin, M., Marcantonini, C. et al., Future Directions for Quantum Technology in Europe - An analysis of policy questions, Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/0891087, JRC141050.

Future Directions for Quantum Technology in Europe

An analysis of policy questions

Lewis, A. M., Scudo, P., Cerutti, I., Travagnin, M. (Fincons SPA) , Marcantonini, C., Ascheri, A., Nardo, M., Di Girolamo, F. E., Zaurino, E., Martinez Cillero, M.

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Abstract

Technologies exploiting phenomena specific to quantum physics are gaining more and more attention. Bold claims are made for their potential, some realistic, others less so. Risks are also perceived, for both information security and physical security, while concern not to miss opportunities is ever present. Major investments are being made, both public and private, and the EU has one of the leading quantum technology initiatives worldwide, in size, breadth and quality.

This report analyses the public and private investment, the scientific and technology progress, and the standardisation maturity of the different quantum technology areas. By raising policy questions, the final aim of the report is to stimulate a debate about the structure and characteristics of EU support for quantum technology, to help to discern the best way forward.

Acknowledgements

We wish to thank our European Commission colleagues Antonia Mochan, Pierpaolo Malinverni and Fabiana da Pieve for thoroughly reviewing the manuscript, Giacomo Badano for checking the section on quantum computing, Julian Wienand for developing the AI tool for analysing the data on funded projects, Gilles Lequeux and Laurent Olislager for helpful comments on the policy background, Daniele Biancardi for contributions to the initial discussions and Fabio Bortolamei for typesetting and layout.

This work was conducted as part of Projects 32260 and 34039 of the JRC's work programme.

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Executive summary

Policy context

The emerging sector of technologies exploiting the unique phenomena of quantum physics is the subject of intensive public and private investment worldwide, including by the EU institutions and Member States. EU support for quantum technology involves several different research and development programmes, large infrastructure projects in quantum communications and computing, and cooperation arrangements with Member States' programmes, some of which are large.

Funding is from the European Commission via the Horizon Europe research and technology programme and the European Research Council, the Digital Europe programme and the Connecting Europe Facility, the High Performance Computing Joint Undertaking, the Chips Act and the Infrastructure for Resilience, Interconnectivity and Security by Satellite (IRIS2); and from the European Investment Bank, the European Defence Agency, the European Space Agency, the European Space Programme Agency and the COST cooperation programme, as well as from national programmes.

In total, as of 2024, funding from these different programmes amounted to more than EUR 2 billion, one of the world's largest concentrations of quantum RTD, albeit significantly fragmented.
Policymakers are now facing several questions about the future of the initiatives and the Commission has just released its new Quantum Europe Strategy.

Key conclusions

Quantum is a new chance for Europe to get its high technology policy right but the international competition is fierce, as is evidenced by data on companies, patents and publications, supply chains and investments. Overall, the EU is well-positioned, with its strong research and innovation ecosystem, and significant investments in the sector. The level of research in terms of publications is second only to the USA or China depending on the quantum sector. The EU is home to a substantial share of quantum companies, accounting for 32% of the total, generally younger and smaller. However, the EU only accounts for 6% of global patenting, with China dominating the field, owning 46% of global patents, followed by the US with 23%.

Although there are advantages at the research and early-stage development levels of encouraging a wide variety of approaches; selection, focus and collective effort are needed to move to higher technology readiness. The EU quantum initiative until now has not been configured to do this and improvements are needed to reach the objective.

It is now urgent to define a path to industrialisation so that the economic potential of the EU's scientific and engineering excellence in quantum technology is realised. The public investments at national and EU level should be consolidated in key strategic technologies or directions, reducing the fragmentation of programmes where possible. Similarly, adequate private sector finance should be attracted at EU and international level.

The EU should aim to strengthen its effort in patenting, standardisation, and in certification where necessary. Protection of innovative solutions and assurance of their interoperability are fundamental for moving to a mature market with international acceptance of the products.

International cooperation brings great benefits because quantum technologies typically require a range of specialised components and skills which can be most efficiently found in the global market. Nevertheless, controls on foreign direct investment and support for European industry must be maintained where necessary to avoid unwanted technology leakage or falling into a position of dependence. A common EU position for trade control on quantum technologies is necessary.

For applications in defence and security, quantum has the potential to provide unique performance gains in position, navigation and timing; secure communications and advanced computing. It is therefore necessary as a matter of defence and security policy to maintain sufficient strength in these areas, to develop an EU supply chain and production capabilities and to impose export controls where appropriate.

1 Introduction

1

The **quantum world** includes individual photons, atoms, electrons and other microscopic particles or small groups of particles. The **classical world** includes everything of everyday size that we can easily see, touch and hear, our own bodies and the tools and devices we use. Our direct experience helps us to understand the physics behind classical phenomena, whereas quantum phenomena are often much less intuitive. Quantum and classical physics differ in the way they describe things, in how well we can measure them, in how the act of measurement changes the objects being measured and in whether or not objects can be considered separate. **Quantum technologies** exploit these differences to achieve performance unattainable by classical means and even to perform tasks that are otherwise impossible. Sensing, measurement and timing, communication, computing and simulation are the areas where quantum technologies offer unprecedented levels of precision, accuracy, security and speed.

While the **First Quantum Revolution** at the beginning of the 20th Century aimed at understanding and modelling physical systems at the atomic and subatomic scale, the present-day **Second Quantum Revolution** exploits and manipulates these systems to create more powerful computational, communication and sensing tools. Research and development are required to fully comprehend the potential applications of quantum and pass from the theory to testing and demonstration, up to a level ready for exploitation.

Worldwide, there is considerable enthusiasm among governments and private investors, to the point that quantum has become one of the most fashionable technology fields today. 2025 has been declared the **UN International Year of Quantum Science and Technology. As a result, a tremendous opportunity exists to drive the field forward**, to realise already-known concepts and to discover new ones. There are also things to be wary of: risks to information security, risks of military application by hostile parties and the risk of being left behind and losing technological competitiveness and autonomy. By no means least, though, is the risk of making unwise investments in directions which a more sober regard could have foreseen to lead nowhere. There are good reasons to be enthusiastic about quantum technology but not to the point of abandoning reasoned judgement.

Quantum technologies have drawn the attention of policy makers, including at the highest level, because of their expected importance for critical areas such as secure communications, computing and defence and their crucial role for competitiveness and economic security. The **European Commission included quantum in its list of ten technology areas critical for the EU's economic securityy**[1] and, more than that, in the priority list of four areas for which an immediate risk assessment needed to be conducted with the Member States, as is now happening. It states: "*Quantum technologies have a vast potential to transform multiple sectors, civil and military, by enabling new technologies and systems that make use of the properties of the quantum mechanics. The full impact of quantum technologies that are being/will be developed cannot yet be fully qualified.*" The EU has invested strongly in the field, building a suite of initiatives targeting different stages of research, development and deployment of quantum tech-nologies, across different programmes, headed by the EU Quantum Flagship and the EU Quantum Communications and Quantum Computing Infrastructures. But there is concern that we have still not established a strong enough position.

The **Draghi report** on EU competitiveness[2] points out that **none of the top ten quantum computing companies in terms of investments is based in Europe**. Moreover, Europe attracts only 5% of worldwide private capital in quantum computing, compared to the 50% of the USA. The report also highlights **critical dependencies for quantum computing platforms** (six critical dependencies across 17 technologies) where fundamental components needed for development and fabrication are only available from outside. China and USA hold technological leadership in most of these components. In its in-depth Analysis section, Draghi places quantum together with high- performance computing, cloud and AI, with the recommendation to improve the EU's position in all of them. The report laments that there are no EU commercial companies comparable in size with the largest ones worldwide. EU companies fail to scale up and to attract funding at early stages causing a gap in later-stage financing, evident especially when comparing

1 Commission Recommendation 2023/2113 of 3rd October 2023 on critical technology areas for the EU's economic security for further risk assessment with Member States (C(2023) 6689 – Annex), 2023, https://eur-lex.europa.eu/eli/reco/2023/2113/oj/

2 Draghi, Mario, "The future of European competitiveness," 2024, Competitiveness Strategy Section, available at: https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en

the EU and USA. The report does, however, also draw attention to the EU's strengths in quantum, which are the size of its public programme, the number of qualified personnel (over 100 000 experts, 231 per million inhabitants) and its high research output. In this landscape, quantum computing is specifically pointed out as playing a crucial role in shaping next generation digital ecosystems.

The 2024 **Niinistö report**[3] on preparedness and readiness, which is concerned with physical security and defence as well as economic security, groups quantum technologies with other high-tech sectors such as advanced semiconductors, AI and biotechnology; **emphasising the need to reduce dependencies and prevent leakage of know-how** to hostile powers. It recognises the innovation potential of quantum computing and its threat to encryption.

The importance of quantum for security applications and the need to enhance its capabilities in EU is emphasised also in the 2025 **EC Communication on European Internal Security Strategy**[4]. In addition to applications in civil security, quantum technologies (in particular quantum computing) are considered critical, foundational and potentially disruptive for defence, as stated in the White Paper on European Defence Readiness 2030.[5] Another White Paper "**How to master Europe's digital infrastructure needs**"[6] of 2024 devotes a section to communication security issues arising from quantum and the available solutions.

At the end of 2023, a group of EU Member States issued a policy statement recognising "the strategic importance of quantum technologies for the scientific and industrial competitiveness of the EU and commit to collaborating on the development of a world-class quantum technology ecosystem across Europe, with the ultimate aim of making Europe the 'quantum valley' of the world, the leading region globally for quantum excellence and innovation."[7]

In this Quantum Declaration, the Member States acknowledge the strategic role of quantum for the EU security and commit to coordinating and supporting the efforts towards EU sovereignty in the sector. The explicit analogy with Silicon Valley in US is to reinforce the mission of nurturing the growth of R&D and business, with the ambition of making EU a global leader for quantum excellence and innovation. Now that the EU Quantum Programme has been underway for several years, it has become clearer what the emerging questions are, and it is time to take stock. The Commission recognised the need for reflection on the future strategy and issued a public Call for Evidence during May 2025.[8]

On 2nd July 2025 the Commission released a Communication "Quantum Europe Strategy: Quantum Europe in a Changing World"[9] setting out its vision. It builds on the 2023 Declaration and on the work of the Quantum Technology Coordination Group, of experts from all Member States.

The EC Joint Research Centre (JRC) issued a policy brief [1] as an immediate response to the Quantum Europe Strategy. We now offer this present report as an additional contribution to the discussion, referring to the Quantum Europe Strategy where appropriate. Numerous studies of the field already exist, some of high quality, so we have endeavoured not to repeat what has already been done. We have drawn on existing studies, on the strategic documents of

3 Niinistö, Sauli, "Strengthening Europe's Civilian and Military Preparedness and Readiness," 2024, available at: https://commission.europa.eu/topics/defence/safer-together-path-towards-fully-prepared-union_en

4 Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on ProtectEU: a European Internal Security Strategy, COM/2025/148, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52025DC0148

5 White Paper for European Defence-Readiness 2030 https://commission.europa.eu/document/download/e6d5db69-e0ab-4bec-9dc0-3867b4373019_en

6 White Paper "How to master Europe's digital infrastructure needs?", https://digital-strategy.ec.europa.eu/en/library/white-paper-how-master-europes-digital-infrastructure-needs

7 European Declaration on Quantum Technologies, available at: https://digital-strategy.ec.europa.eu/en/library/european-declaration-quantum-technologies

8 Call for evidence for European Declaration on Quantum Technologies, available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14675-Quantum-Strategy-of-the-EU_en

9 European Commission, "Quantum Europe Strategy," July 2025, https://digital-strategy.ec.europa.eu/en/library/quantum-europe-strategy

the EU and other programmes, project information, financial data and patents data, to point out what we consider to be the most important policy issues today.

In this report, we emphasise the **importance of the match between technology concepts and use-cases, scalability and societal relevance**. We hope to stimulate the discussion of these questions among participants in the EU programme and within the EU institutions.

1.1 Quantum Technologies

Quantum technologies find applications in computing and simulation, communication and sensing, with overlaps and communalities among these application areas, especially with regard to the required enabling technologies. For a comprehensive assessment of the state of the art and its applications, as well as detailed roadmaps for envisaged technical progress, we refer the reader to the Strategic Industry Roadmap of the European Quantum Industries Consortium (QuIC)[10], focusing instead, in this section, on the technical aspects of these four areas which are relevant for policy decision-making.

1.1.1 Quantum computing and simulation

The current generation of quantum computers is known as NISQ, Noisy Intermediate-Scale Quantum. The term was coined by John Preskill in 2018 [2] to signify their limited capabilities. It is generally accepted in the community that such systems have some research value, but are unable to solve industry-relevant problems, due to their intrinsic noise levels. The consensus is that NISQ systems are best suited for the execution of a rather small class of algorithms aimed at finding the minimum energy state of a physical system. Their common features are their limited number of qubits (e.g., see Fig. 1 in the QuIC report[10]) and their shallow ''depth'', meaning that they can execute a small number (in the range of tens) of qubit gate cycles.

Several NISQ platforms are currently being investigated (the main ones being qubits based on superconducting circuits, atomic spins, trapped ions, neutral atoms, photons, and topological states of matter) **and research is ongoing in several alternative directions, without a clear winner yet**. EU-funded projects cover all of them, and the European Quantum Industry Consortium has detailed technology development roadmaps that span to 2035. It must be noted that each one of these lines of research has its own supply chain, even though some enabling technologies are in common.

Several NISQ quantum processors with up to one hundred noisy qubits are available for rent on the cloud, and a particular kind of quantum computer, called quantum annealer, specialised in addressing optimisation problems, has been sold commercially since 2011[11]. Quantum annealers are examples of quantum simulators, machines with similar properties to other quantum systems of interest but easier to programme and control through a set of tuneable parameters. This approach may be more feasible than using NISQ gate-based machines and is also promising for some mathematically-hard classical simulations., as explained in the QUIC Roadmap.

Over the years, several **claims** have been published that **a NISQ machine can perform some computational task more efficiently than its classical counterparts, called "quantum advantage"**. These claims all referred to the solution of a s**pecially contrived optimisation problem**, with no general usage beyond it demonstrated. In some cases, the term of comparison was brute-force classical calculation, instead of the best available classical alternatives and algorithms. Consequently, several papers claiming to demonstrate quantum advantage have been subsequently disproved. To give some examples, the 2019 Google claim on "Quantum supremacy using a programmable superconducting processor" [3] was confuted by IBM with "Leveraging Secondary Storage to Simulate Deep 54-qubit

10 European Quantum Industry Consortium (QuIC), "Strategic Industry Roadmap (SIR)", 2024, available at: https://www.euroquic.org/wp-content/uploads/2024/02/PUBLIC-version-Strategic-Industry-Roadmap-2024.pdf

11 https://www.dwavequantum.com/

Sycamore Circuits" [4] and again later on by a team from the Chinese Academy of Science with "Solving the Sampling Problem of the Sycamore Quantum Circuits" [5]. The 2023 IBM paper on "Evidence for the utility of quantum computing before fault tolerance" [6] was contradicted by "Efficient Tensor Network Simulation of IBM's Eagle Kicked Ising Experiment" [7], while the D-Wave publication titled "Beyond-classical computation in quantum simulation" [8] was confuted by "Dynamics of disordered quantum systems with two- and three-dimensional tensor networks" [9] and by "Challenging the Quantum Advantage Frontier with Large-Scale Classical Simulations of Annealing Dynamics" [10].

Therefore, **undisputable evidence for the capability of quantum computing before fault tolerance to generate economic value has yet to emerge.** The European Quantum Industry strategic roadmap published by the European Quantum Industry Consortium10 acknowledges that "demonstrating quantum advantage in practical applications remains a primary objective for global quantum computing projects". Claims by commercial vendors about available processors already being useful for practical applications are therefore to be taken with a (big) pinch of salt.

When considering the electronic digital computing, a self-sustained cycle of technological progress took place starting from the '50s, because even the first rudimentary and expensive machines were clearly superior to the alternative of hand-executed calculations. The situation is different with quantum computing, and **it is possible that practical advantages will materialise only after (or if) full fault tolerance will be achieved. However, technology progress in quantum computing hardware is beyond doubt, according to several different quantitative metrics** (e.g. qubits number, error rate of two-gate ports, error correction), and many efforts to reach satisfactory benchmarking are ongoing [11].

Transitioning from the NISQ era to the execution of general-purpose algorithms, such as the Shor algorithm for integer factorisation [12] and the Grover search algorithm [13], **will require noiseless quantum computers**. It must be emphasised that the required technological scale-up is extremely challenging and has many unclear aspects and daunting hardware requirements, for instance regarding qubit connectivity. Most quantum algorithms require thousands of logical qubits to address practical applications, with **each logical qubit requiring thousands of physical qubits with lower noise and fidelity better than the state of the art**. If the current error correction techniques are to be used, the number of physical qubits will have to reach the (at present unimaginable) range of millions. Progress in error correction is taking place (see e.g. Google's results with their Willow processor [14], and [15] for an alternative approach) but a technology platform able to scale up from the ~100 physical qubits of present-day quantum processors has yet to be identified. It must therefore be admitted that, without very substantial progress in qubit number and quality, quantum computing will remain only a scientific research topic [16].

However, some countries have already taken development decisions and made their choice. For example, Australia has committed almost AUD 1 billion (about EUR 550 million) to PsiQuantum to build a fault-tolerant quantum computer based on photonic qubits, leveraging the existing materials, reliability, volume and precision of standard semiconductor manufacturing processes.[12] PsiQuantum is therefore building thousands of wafers (each one with hundreds or thousands of quantum chips), testing the production cryogenic cabinets and planning to develop fault-tolerant algorithms to deploy a useful quantum computer in 10-years' time.[13] Conversely, the High Performance Computing Joint Undertaking (EuroHPC JU) which is co-funded by the EC is targeting the simultaneous deployment of eight fairly small quantum computers in different EU countries, based on different technologies, with investment in the range of EUR 5-25 million each.[14]

From computational theory, it has been demonstrated that the quantum computing paradigm can provide exponential speedup only for a limited set of problems, and that for several more commonly encountered problems the only possible quantum advantage is polynomial. This state of affairs has been the object of many reviews (e.g., [16], [17]). In addition to cryptoanalysis, notable use-cases targeted by quantum algorithms are Monte Carlo

12 https://www.psiquantum.com/news-import/psiquantum-to-build-worlds-first-utility-scale-fault-tolerant-quantum-computer-in-australia

13 PsiQuantum, "A fast path to useful, error-corrected quantum computing," available at: https://www.psiquantum.com/blueprint

14 List of quantum computers funded by EuroHPC JU available at: https://eurohpc-ju.europa.eu/eurohpc-quantum-computers/our-quantum-computers_en

simulations and linear equation solving, hence machine learning. The real impact of the theoretically attainable advantage will be determined in practice by the size and speed of available hardware. Moreover, it must be emphasised that only for mathematically very hard problems do those algorithms reasonably deliver an advantage over classical machines, GPUs and parallel computing, which also are advancing rapidly. For example, shallow algorithms can be efficiently simulated with rapidly progressing techniques, based for instance on tensor networks. Progress with other computational approaches can erode the areas where quantum computing can be useful: to give an example, protein folding was considered a typical use case, but artificial intelligence (AI) seems to have provided a boost with respect to previous state of the art [18]. Therefore, it is very hard to predict when, or even if, quantum computers will prove useful in solving real world problems, and it is possible that they will have a significant importance only for a limited number of specialised tasks. There is ample debate in the community with no clear-cut conclusions available.

To conclude on a more optimistic note, it must be acknowledged that **quantum computing has sparked healthy competition between classical and quantum algorithms and their simulation**. Several shallow algorithms can be efficiently simulated using tensor networks, a classical method that can efficiently simulate a large number of qubits, with known error. In parallel, **we witness substantial progress in the so-called quantum inspired algorithms that can be run on classical computers with clear advantage**. These areas of research will beyond doubt allow for progress in many applications in the short term. Apart from mathematics and algorithms, it is also beyond doubt that quantum computing research has sparked many innovations in the technology platforms being investigated and the associated enabling technologies.

1.1.2 Quantum communications

The invention of **Shor's algorithm** [12] in 1994 made it clear that quantum computing represents a major risk for communications security: public-key cryptographic algorithms of widespread use for authentication and encryption, such as RSA (Rivest–Shamir–Adleman) and ECC (Elliptic Curve Cryptography) and key exchange, such as DH (Diffie-Hellman) and ECC-DH would be impacted beyond salvaging. However, it has long been known that leveraging quantum physics principles allows one to establish whether or not an interception attempt is going on during a symmetric encryption-key exchange, via a technique called **quantum key distribution (QKD)**. QKD is a key agreement scheme which in principle can solve the encryption preliminary step of providing two legitimate players a private key secure against any possible attack, also by a quantum computer. This technique, first proposed in 1984 and experimentally demonstrated in 1991, has reached market maturity and is currently being sold by different firms with different protocols and implementations. However, several National Security Agencies (e.g. US National Security Agency[15], Agence nationale de la sécurité des systèmes d'information[16], Bundesamt für Sicherheit in der Informationstechnik[17], as well as others in UK, NL, SE) have highlighted the open issues still affecting QKD. One national intelligence service, in the Republic of Korea, has approved a QKD system. Rebuttals have been given by the QKD scientific community [19], [20], including to the Commission in the early discussions for the European Quantum Communication Infrastructure (EuroQCI) [21] and to the EU standardisation bodies[18] but sceptical views persist, see [22]. Here we mention in particular:

- The range limitation. Currently, this can only be overcome by recovering the key in classical form and retransmitting it at "trusted nodes", which have to be physically secured and kept under surveillance to prevent an adversary obtaining the key, with related risks of security breaches. Meanwhile, new QKD protocols, quantum repeaters and satellite-based links are being explored as solutions, with the question of their long-term performance being still open.

15 National Security Agency, "Quantum Key Distribution (QKD) and Quantum Cryptography (QC)" webpage, available at: https://www.nsa.gov/Cybersecurity/Quantum-Key-Distribution-QKD-and-Quantum-Cryptography-QC/

16 ANSSI – Technical Position Paper: QKD v2.1, "Should Quantum Key Distribution be Used for Secure Communications?,"available at: https://cyber.gouv.fr/en/publications/should-quantum-key-distribution-be-used-secure-communications

17 "Position Paper on Quantum Key Distribution," available at: https://www.bsi.bund.de/SharedDocs/Downloads/EN/BSI/Crypto/Quantum_Positionspapier.pdf?_blob=publicationFile&v=4

18 CEN-CENELEC Joint Technical Committee 22 Quantum Technologies, "QKD and PQC - An analysis and comparison of both technologies", to be published

- The need for a separate authentication step to be made, for example with post-quantum algorithms, which undermines the claim of unique advantage for the quantum-based solution. The rebuttal is that, in QKD, breaking the security of the authentication exchange after it has taken place does not allow an attacker access to the key, so that he would have only a very brief opportunity to conduct his attack.
- The fact that the practical security level is hard to quantify, since it depends on non-ideal hardware and implementation. The debate centres on whether this situation is really any worse for QKD than for classical solutions.
- The still long roadmap for standardisation and certification of QKD devices, and their subsequent regulation, see Chapter 4.
- The integration with existing telecom networks in not immediate, so that QKD cannot be considered a plug-in solution but requires specific adaptations. There is no dispute about this point; QKD advocates point to use cases where it is justified and feasible. Deployed optical networks can host quantum transmissions on a separate band of the same fibres or on a different fibre and can accommodate technical solutions enabling the quantum signal to bypass the intermediate amplifiers.
- The need for specialised, high-cost hardware especially when scaling in large networks. However, scale economy and technological advancements can help overcome this cost barrier in future. A solution may be provided by the replacement of bulky products with photonic integrated QKD chip platforms in future. The field of integrated photonics has rapidly progressed in recent years approaching millimetre-scale footprints with multi-photon state generation, and integrated photonics may enable miniaturised, low-cost QKD solutions[19], see also [23], [24].

Despite these issues, China and more recently the EU have been investing in QKD. China deployed a large-scale integrated space-to-ground quantum communication network [25], [26], [27], [28]. Similarly, the EU supports both fibre-based and satellite-based QKD in the European Quantum Communication Infrastructure (EuroQCI, see Section 2.3).

In the USA, there is currently no national-scale QKD infrastructure project [29]. After earlier deployments in 2005-2010, several research projects and some deployments are ongoing. Stony Brook University, in cooperation with Brookhaven National Laboratory, deployed a 250 km network for quantum communication and quantum internet testing, distributing entangled photons between Long Island and Manhattan[20]. The network is being extended to reach the Bronx and Brooklyn and is co-funded by venture capital and public funds through the Long Island Investment Fund. Recent results and progress in performance have been published [30].

Quantum-based cyber hacking requires fault-tolerant quantum computing, which as previously shown is still many years away. However, as clarified especially in [31], **the need to address this risk is urgent because of the time required for security upgrades in the existing infrastructure and the time interval for which data needs to remain confidential**, given the possibility of "store now, decrypt later" attacks. In 2016 the US National Institute of Standards and Technology (NIST) initiated a process to develop and standardise public-key cryptographic algorithms able to protect sensitive information in widespread real-world use cases well into the foreseeable future, including against quantum computing attacks. These are known as quantum-safe or, more cautiously, quantum-resistant algorithms and the field is termed post-quantum cryptography (PQC). A first set of standards[21] has recently been released. The main approaches are lattice-based, hash-based and linear-code-based systems. Lattice-based systems have so far tended to be favoured in the NIST competition, but one of the two recently issued standards for digital signature is hash-based. Problems to be overcome in integrating quantum-resistant algorithms include large key size and high processing requirements. Although considerable progress has been made, introduction of PQC may require substantial hardware investments for organisations using it at scale; it seems that the transition to PQC will

19 ID Quantique, "Photonic Chip-based QKD achieves higher transmission speeds," available at: https://www.idquantique.com/photonic-chip-based-qkd-achieves-higher-transmission-speeds/#:~:text=In%20a%20research%20project%20led,priority%20in%20their%20national%20strategy

20 See the website of Figueroa research group at Stony Brook university, available at: https://www.stonybrook.edu/commcms/physics/figueroa-research-group/news

21 NIST, "Post-Quantum Cryptography" webpage at: https://csrc.nist.gov/projects/post-quantum-cryptography

not be a simple drop-in replacement for RSA and ECC. Furthermore, although all the main approaches come from well-established ideas which existed simply as classical systems, before being proposed for quantum resistant ones, there is relatively little experience with any of them. The first hurdle is to show that they are invulnerable to classical attacks; some promising candidates have already fallen at this stage. In 2022 one of the four final NIST candidate algorithms was unexpectedly broken [32].

The quest for quantum-safe algorithmic cryptography is bound to remain an open problem since unexpected mathematical breakthroughs are always possible. Algorithms introduced industry-wide may have to be replaced at short-notice, perhaps repeatedly, a requirement termed "cryptographic agility". Continuing financial support for research in quantum safe algorithms is vital, which the EC does through Horizon Europe[22] but the limiting factor is skilled workforce rather than money: the number of experts able to work seriously on the topic is small. Targeted funding can help for the more general aspects of PQC, such as its deployment and integration in cryptographic systems in networks.

Despite these unknowns, it is prudent for organisations with high IT-security requirements, including government agencies and critical infrastructure operators, to prepare to transition to quantum-resistant algorithms now, as the EC officially recommends[23].

JRC has interacted both with developers of QKD systems and exponents of the PQC algorithmic approach. Our informed position is that QKD is not a general solution to the threat to cryptography from quantum computers but can contribute in certain use cases, providing that technological hurdles can be overcome. An essential requirement for QKD to be applicable is that a suitable infrastructure is available (see Section 2.3 on EuroQCI) and should be flexible enough to provide other services in future. Quantum communications is indeed more than the exchange of encryption keys as in QKD, and entanglement distribution could be an effective instrument to scale up reducing the use of trusted nodes, support different cryptographic tasks and also distributed quantum computing as the power of quantum processors increases exponentially with the number of qubits. **In the framework of the European High Performance Computing Joint Undertaking (EuroHPC-JU) which procured eight quantum computers across EU, a quantum communication network linking all or most of them would exert a huge leverage effect.** It must however be acknowledged that this is a long-term effort, for which critical enabling technologies, and in particular field-deployable quantum repeaters, are still missing.

1.1.3 Quantum sensing

The first thing to be noted is that **quantum sensing attracts much less investment than quantum computing and quantum communications**, despite being for several aspects a much more mature area. According to McKinsey 2024 data[24], until now it gathered USD 0.7 billion investment worldwide, about 10% of quantum computing investment (USD 6.7 billion) and 60% of quantum communications investment (USD 1.2 billion).

"Quantum sensing" is a broad term, typically employed [33] to describe:

- The use of a quantum object characterised by quantised energy levels (e.g. electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions) to measure a physical quantity.
- The leveraging of quantum coherence (i.e., wave-like spatial or temporal superposition states) to measure a physical quantity.
- The use of quantum entanglement to improve the sensitivity or precision of a measurement beyond what is possible classically.

22 In 2024, through call HORIZON-CL3-2024-CS-01-02, with indicative budget EUR 23.40 million.

23 Commission Recommendation (EU) 2024/1101 on a Coordinated Implementation Roadmap for the transition to Post- Quantum Cryptography, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401101

24 McKinsey, "Quantum Technology Monitor," available at: https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantum-technology-monitor-april-2024.pdf

To highlight the variety of physical platforms which can be leveraged for quantum sensing we mention neutral atoms (in the form of optical molasses, Bose Einstein condensates, warm vapours), trapped ions, Rydberg atoms, and solid-state systems (nitrogen vacancies in diamonds, semiconductor quantum dots). Also, it is important to note that **there is a significant difference in technology readiness level (TRL) between different types of quantum sensors**. Some of them have been commercially available for a long time and a few have demonstrated high impact on national security alongside commercial applications. A notable example is that of atomic clocks: they started to be commercially sold in the '60s, have underpinned the deployment of Global Navigation Satellite System (GNSSs), and are seeing continuous progress covering both high-end metrological uses and industrial applications. As detailed in [34], [35], some novel quantum sensing devices have reached a very high TRL and are commercially available (e.g. cold atom gravimeters), others are on the cusp of market availability (e.g., optically-interrogated magnetometers based on warm atomic vapours, solid state magnetometers based on nitrogen vacancies in diamond), while some others are still to be considered low-TRL prototypes (e.g., Rydberg atoms for radiofrequency detection) even if demonstrated in the field. Some quantum sensing ideas are based on physical principles that have not yet been clearly demonstrated to have practical utility (e.g. quantum radar).

The above considerations show that quantum sensing is fragmented along different technological platforms and is applicable to very disparate use cases. Even those with promising near-term opportunities of transitioning from laboratory demonstrations to real world applications need to overcome these challenges:[25]

- Integration into existing systems can be difficult, and pros and cons of different approaches are difficult to compare.
- Bridging the gap between research and industry by developing rugged and field-deployable products is difficult, time-consuming, and costly.
- Government-sponsored technology development often stops at proof-of-concept demonstrations and does not promote technology maturation up to the commercial stage.
- Sometimes dedicated and customised enabling technologies with limited market are required, hindering the development and increasing the cost.
- The access to testbeds and platforms for high-fidelity emulation of realistic operating conditions is often limited and expensive.

All of the above indicates that a deep engagement is required between quantum sensor developers and prospective end users.

To give an example of European know-how and capabilities, we highlight that in 2023 a magnetometer based on warm atomic vapours was launched towards Jupiter in ESA's JUICE mission [36] and that a similar instrument developed by the Italian space agency has been flying since 2018 aboard the Chinese seismo-electromagnetic satellite [37] which is expected to end in December 2025. However, the US seems to be closer to commercial exploitation of these magnetic sensors,[26] having built a very compact and low-cost device leveraging the enabling technologies developed more than 20 years ago for their chip-scale atomic clock.

As shown in Section 3.8 on scientific publications, the EU is well positioned in **sensors based on cold atom interferometry**: several advanced prototypes of gravimeters have been developed, and an EU-made product is commercially available; accelerometers, gyroscopes, and inertial navigation units are being developed (also with funding from the European Defence Fund), although the USA and UK are at the leading edge with in-field testing. NASA's Cold Atom Lab on board the International Space Station has studied, since 2018, ultra-cold atom gases in a micro-gravity environment.[27] NASA is active also with its Quantum Gravity Gradiometer Pathfinder (QGGPf) for atom interferometry

25 Quantum Economic Development Consortium (QED-C), "Quantum sensing use cases,", September 2022. https://quantumconsortium.org/publication/quantum-sensing-report-2022/

26 See for instance the chip-scale magnetometers by NIST at: https://www.nist.gov/noac/technology/magnetic-and-electric-fields/chip-scale-atomic-magnetometers

27 Webpage of Cold Atom Lab at NASA, available at: https://coldatomlab.jpl.nasa.gov

sensing in space, in collaboration with industry partners AOSense, Infleqtion, and Vector Atomic. ESA is now deploying a cold-atom clock built by the French space agency CNES in the International Space Station. The German space agency DLR is working on characterising Bose-Einstein condensates in space. The EC is funding a preparation mission for a satellite dedicated to the in-space deployment of a cold atom accelerometer.

Several projects involving **nitrogen-vacancy (NV) centres in diamond for sensing applications** have been funded by the EC, contributing to raising the interest of large firms such as Bosch and Thales and spurring the formation of an ecosystem of startups (NVision, QZabre, Diatope, Quantum Diamond), which are targeting industrial applications. Horiba Qnami (headquartered in Japan, but leveraging Swiss know-how) is already marketing an NV magnetometric imaging system to be used in semiconductor manufacturing, and Bosch has set itself a 10-year timeframe for NV sensors commercialisation. In the US, Lockheed Martin has built a prototype of a NV magnetometer to be used for magnetically assisted navigation.

Rydberg atom sensors are conversely a field where the US seems to be firmly at the leading edge: several DARPA projects have already led to in-field tests, and some commercial products are being sold by SME such as Infleqtion and Rydberg Technologies. In addition to military applications (such as radiofrequency spectral analysis for signal intelligence and military radios), Rydberg atoms are important also for metrology and space applications, where they can be used as antennas and receivers for direct RF-to-optical conversion in multi-frequency radars.

As a general assessment, it can be said that **the EU is well placed in quantum sensing against strategic competitors for some of the current high-value, low-volume instruments which are starting to enter the market**. The critical question is whether it can maintain its status when it comes to scale-up of production, given the lack of a low-cost supply chain and / or lack of strategic investment into large scale production capabilities which can reliably supply quantum technology developers. This is in part a cultural issue, as EU companies are often more conservative in investment decisions, waiting for a clear market pull signal. The US has the advantage of large early adopter markets in the defence sector (for example, Vector Atomics is already commercializing a field- deployable compact optical atomic clocks for autonomous PNT), and China has the advantage of strategic government investment decisions in new technology production capacity. In the EU some critical markets (e.g. defence) are still fragmented along national borders, and Member States will try to develop and maintain national champions in manufacturing capabilities that they deem too important to share. Based on these considerations, the Quantum Europe Strategy[9] plans the publication of a Quantum Sensing Roadmap by 2026 and the deployment of a distributed system of gravimeters and a Quantum MRI infrastructure.

Market pull and strategic technology support are essential to spur the development of an EU-based dedicated supply chain which presently serves only tiny markets for niche applications, but which future developments are hard to predict. The enabling technologies developed by the US in the 2000s for the first chip-scale atomic clock (custom lasers, alkali vapour microcells, micro- integrated control systems, etc.) are now being used also for chip-scale magnetometers based on thermal atoms – which will be used for autonomous navigation, sensing of submarines and space-based magnetometry.

Indeed, **the market size for some quantum sensors will become significant only when smaller, integrated, cheaper versions become available**. Developing miniaturised components for such instruments requires large-scale investment in high-end manufacturing capabilities. To ensure the low-cost reliable manufacturing needed to commercialise competitive products **the current model of laboratory-scale fabrication of small batches of highly customised prototypes must be superseded by an approach where the production of some critical items is concentrated at EU level**.

1.2 Report organisation

This report aims to provide an overview of the EU position in this quantum landscape, from the scientific, technological, and economic point of view, highlighting the existing and future challenges. For this scope, the various EU programmes financing quantum technologies are presented and discussed in Chapter 2. The public and private investment in the quantum areas (i.e., computing and simulation, communication and sensing) are investigated in Chapter 3, by comparing the EU against the other major countries. In addition, the same chapter assesses and compares the level of scientific progress and innovation in the EU, by collecting key indicators on the publications and patents in EU versus the rest of the world. Chapter 4 discusses the ongoing activities and the challenges in the standardisation and in the trade control of quantum technologies. Throughout these sections, we have highlighted some points for debate that, in our opinion, would require attention from policy makers and organisation management. The aim is to encourage a broader discussion, to enable further improvements, innovation, and investments in the sector, in the global interest of the EU.

Based on the analysis of the EU position in the quantum landscape, we formulated recommendations for key decisions to be taken at the policy level in Chapter 5. Finally, the conclusions are presented in Chapter 6.

2 EU Programmes financing quantum technology

2

The EU has launched a comprehensive set of initiatives to support the research, development, and commercialisation of quantum technologies (Figure 1).

Dedicated Quantum Initiatives

- **European Quantum Flagship** is a large-scale, long-term initiative coordinating quantum research and innovation.
- **QuantERA** is a network of research funding organisations supporting transnational quantum technology projects.
- **European Quantum Communication Infrastructure (EuroQCI)** is focused on building a secure quantum communication network across Europe.

Broader Technological Initiatives

Quantum technologies also benefit from larger EU initiatives that encompass a wider range of advanced technologies:

- **European High Performance Computing Joint Undertaking (EuroHPC JU)** supports the development of cutting-edge supercomputing infrastructure, which includes quantum computing.
- **Chips Joint Undertaking (EuroHPC JU)** aims to strengthen Europe's semiconductor ecosystem, including components relevant to quantum technologies.
- **Photonics 21** aims to promote and develop the field of photonics in Europe., which is relevant also for quantum technologies.
- **EURAMET**, the European Association of National Metrology Institutes, promotes technological development in the field of measurement, including with quantum technologies.

General Support for Innovation

Beyond specific technological-focused initiatives, quantum technologies receive support through general EU initiatives for technological development and commercialisation:

- **European Innovation Council (EIC)** provides funding and support for innovative projects, including those in quantum. The EIC is a key component of the Horizon Europe's Pillar III – Innovative Europe.
- **European Investment Bank (EIB)** offers financing for quantum-related ventures.
- **European Defence Fund (EDF)** supports research and development in defence capabilities, which can include quantum applications.

Research Funding

The EU also fosters foundational research in quantum technology through various funding schemes:

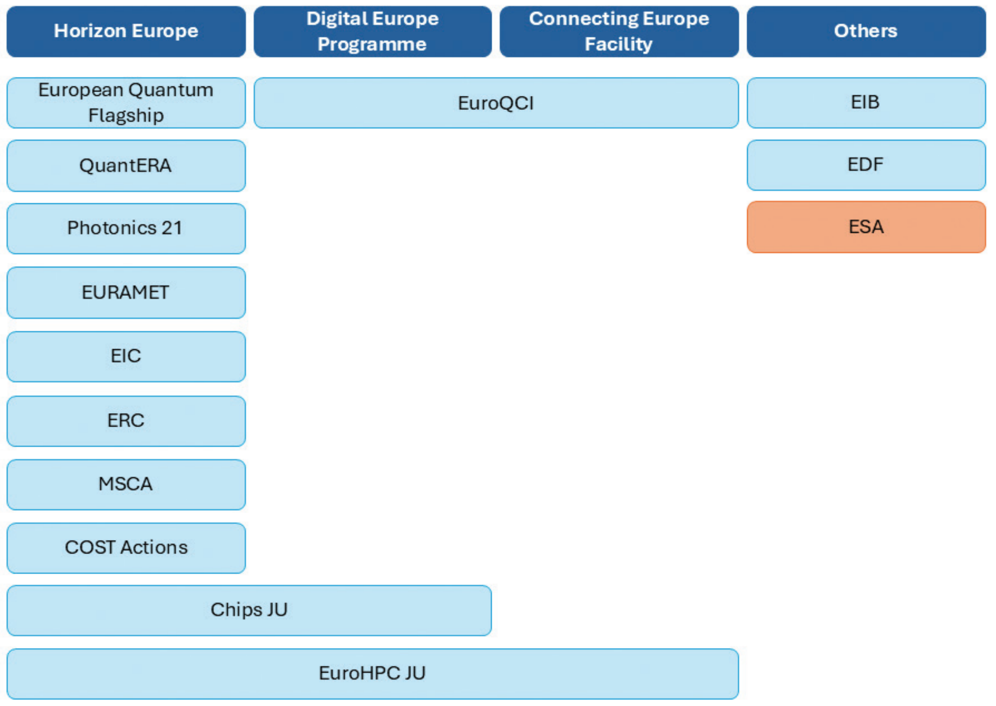
- **European Research Council (ERC) grants** support research across all fields, including quantum technology and quantum physics crucial to its advancement.
- **Marie Skłodowska-Curie Actions (MSCA) fellowships** fund researcher career development also in the quantum areas. ERC grants and MSCA fellowships are key components of the Horizon Europe's Pillar I – Excellent Science.
- **European Cooperation in Science and Technology (COST) Actions** promote scientific and technological cooperation, including quantum-related networks.

European Space Agency Role

In addition to the EU's direct initiatives, the **European Space Agency (ESA)** carries out activities for the study and development of quantum technologies in space. While financed in part by the EU, the ESA is not an EU body. Its efforts primarily focus on **quantum sensors** and **space-to-Earth quantum communication links**.

While these are the main EU initiatives funding quantum technology projects, as shown in Section 3.1, there are other quantum projects that receive funding through other EU instruments, particularly within the Horizon Europe framework. The remainder of this chapter details these EU initiatives. The ESA activities on quantum technologies are discussed at the end of the chapter.

Figure 1 Overall structure of EU funding for quantum technology research and development



Source: JRC

Points for debate:

- Is having several different programme models optimal or does it increase the risk of having overlapping instruments?
- Does it provide flexibility, so that different types of European project can find their right scheme, or does it merely increase administrative costs and the time researchers must take to learn their funding options?

2.1 European Quantum Flagship

The Quantum Flagship[28] is a research and innovation initiative launched by the EU in 2018, with the goal of developing and commercialising quantum technologies. Specifically, the goal of the Quantum Flagship is to consolidate and expand European scientific leadership and excellence in quantum technologies, while also kick-starting a competitive European industry in this field by promoting Europe as a dynamic and attractive region for innovative research, business, and investments. The name was adopted from EU programmes on graphene and the human brain, with the idea that a similar approach would be suitable for quantum technology.

The Quantum Flagship comprises a coherent set of research and innovation projects selected through a peer-review process around four main areas: quantum computing, quantum simulation, quantum communication, quantum sensing and metrology.

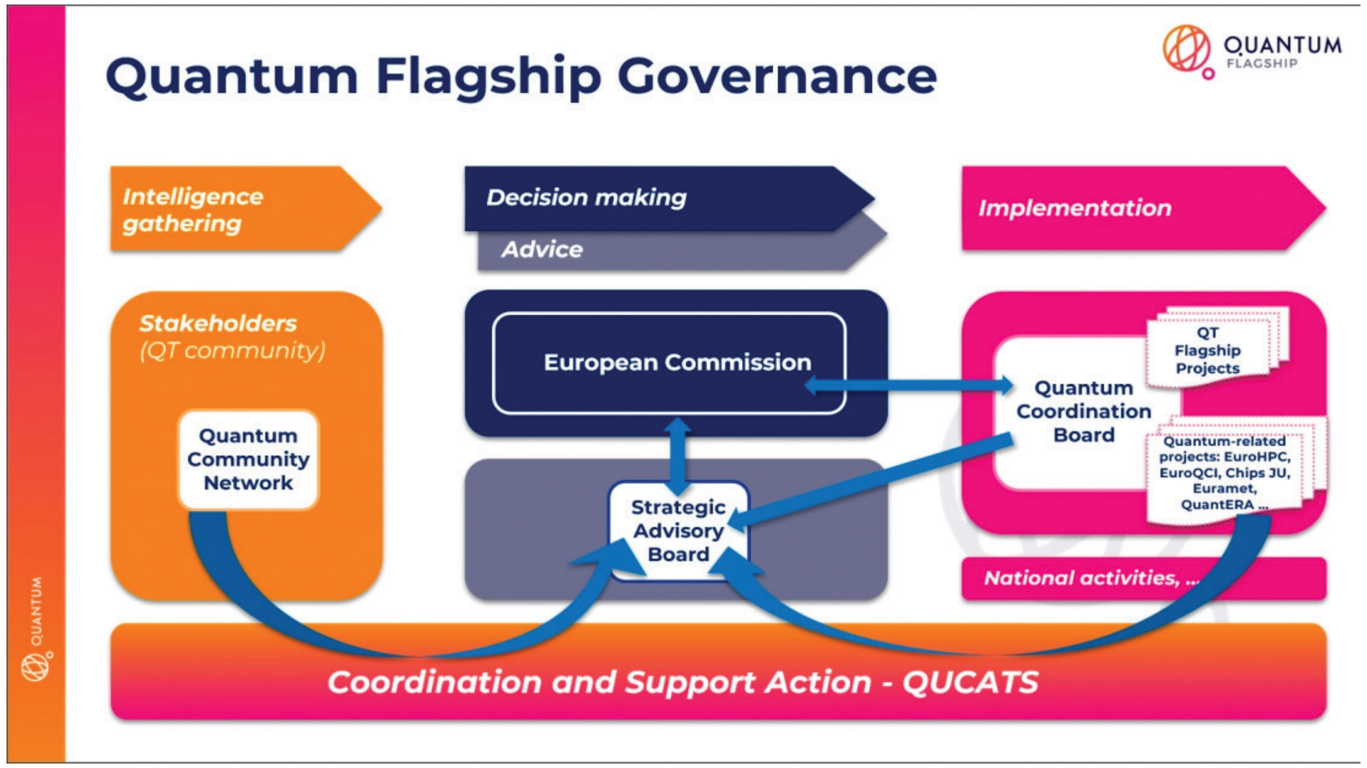
28 Quantum Flagship website at: https://qt.eu/

It is governed by a somewhat elaborate structure, involving multiple stakeholders and organisations, as shown in the governance organigram in Figure 2.
The main governance bodies are:

- Strategic Advisory Board (SAB): it provides guidance and oversight to the Quantum Flagship, ensuring its progress and alignment with the Strategic Research and Industry Agenda (SRIA). The SAB's membership is comprised of 40% from industry, 40% from academia, and 20% from research and technology organisations.
- Quantum Coordination Board: it coordinates and aligns the EU initiatives in Quantum Technologies. Its responsibilities include harmonizing project activities, identifying common themes, and proposing unified solutions throughout the Quantum Flagship's duration.
- Quantum Community Network: it represents the EU Quantum Technology communities; it comprises one member and one deputy member per country. These experts synchronise the Flagship with national initiatives, engage national stakeholders, and serve as primary contacts for Quantum Flagship-related inquiries.

Moreover, a Coordination and Support Action (QUCATS)[29] serves as the Quantum Flagship Secretariat, supporting the three governance bodies, organising stakeholder engagement. The Quantum Flagship is largely managed by the technology community itself, with the European Commission exercising a lighter involvement than in other parts of Horizon Europe. While the Commission does retain decision- making powers as part of its responsibility for management of EU funds, it is the Quantum Coordination Board that implements the initiative.
The Quantum Flagship has been allocated approximately EUR 1 billion in funding through the Horizon 2020 and Horizon Europe programmes, over a period of 10 years. To 2024, the Quantum Flagship has supported more than 60 projects, investing about EUR 450 million from EU funds (see Section 3.1).

Figure 2 Quantum Flagship Governance



Source: Quantum Flagship website[30]

29 Website of QUCATS at: https://qt.eu/projects/csa-projects/qucats

30 Governance and structure of the Quantum Flagship, available at: https://qt.eu/structure-governance/

Points for debate:

- How successful has the governance model been? Should it be retained or modified for the remainder of the initiative?
- Early Flagship calls returned a high number of basic research proposals, and the website's statistics, for funded quantum projects, Flagship and other, show a similar tendency, especially before 2022. Should the Commission intervene to encourage higher TRL work?
- Are the Framework Partnership Agreements a stabilising factor? How have they been received by the research community?
- Is the funding for the Flagship too small, so it has insufficient impact, or is it too big so it takes too many resources from other quantum initiatives?
- Does the SRIA really define an agenda or just catalogue activities? Is the document becoming too long?

2.2 QuantERA

QuantERA[31] is a European network of 41 research funding organisations from 31 countries, including EU Member States, the UK, Switzerland, Norway, and Turkey. Its primary objective is to support and subsidise the development of quantum technologies. To date, QuantERA has funded 101 projects, through Calls for Proposals in 2017, 2019, 2021 and 2023, across various quantum technologies, including quantum communication, sensing, and computing, as well as advanced architectures and quantum algorithms, with a total budget of EUR 117 million. The budget was partially financed by the Commission with two ERA-NET co-funds from Horizon 2020: QuantERA I[32] (2016-2022), which received an EU contribution of EUR 11.5 million, and QuantERA II[33] (2021-2026), which received an EU contribution of EUR 15 million. QuantERA has announced its 2025 Call for Proposals, partially supported by the Commission under the Horizon Europe Framework with the QUANTERA III grant agreement.[34]

Compared to the Flagship, QuantERA operates on a significantly smaller scale, with a focus on funding high-quality research through transnational calls. This approach aims to develop synergies in European research in quantum technologies, fostering collaboration and innovation among different countries across the European Research Area (ERA). QuantERA has a relatively simple governance structure, with coordination provided by the National Science Centre (NCN) in Poland, a call secretariat management by the Agence Nationale de la Recherche (ANR) in France. Additionally, QuantERA has a Strategic Advisory Board composed of up to 18 prominent researchers, who provide guidance and expertise to the initiative. To avoid duplication of research activities, QuantERA requires that funded projects do not duplicate research already supported by the Flagship or by previous QuantERA calls.

Points for debate

- Is QuantERA adequately integrated with the rest of the EU initiatives?

31 QuantERA website at: https://quantera.eu/

32 QuantERA project on CORDIS website at: https://cordis.europa.eu/project/id/731473

33 QuantERA II project on CORDIS website: https://cordis.europa.eu/project/id/101017733

34 QuantERA III project on CORDIS website: https://cordis.europa.eu/project/id/101212998

2.3 European Quantum Communication Infrastructure (EuroQCI)

The European Quantum Communication Infrastructure (EuroQCI)[35] initiative aims to create a secure quantum communication network spanning the entire European Union, including its overseas territories. It was launched in 2019 via the EuroQCI Declaration, which has now been signed by all 27 EU Member States. It is a collaborative effort between the European Commission, the Member States, and the European Space Agency (ESA) for the space segment, financed through the Digital Europe Programme (DEP) and the Connecting Europe Facility (CEF).

EuroQCI will consist of a terrestrial segment with fibre-based links within Member States and cross- border, and a space segment with satellites links managed by ESA. The final target is a fully operational system, integrated with the second generation of IRIS², the new EU space-based secure communication system.[36] The first service will be QKD, with use-cases in safeguarding sensitive data in critical infrastructures, such as governmental institutions, data centres, hospitals, and energy grids.

Regarding the terrestrial segment, the first implementation phase started in January 2023, supported by DEP. Below, we detail the projects involved for the terrestrial segment and, based on the analysis described in Section 3.1, we present information on the EU funds allocated to them through 2024.

- 6 industrial projects aimed at developing and maturing the QKD technological building blocks for the EuroQCI, with a budget of EUR 48 million, of which EUR 30 million is allocated by DEP.
- 26 national projects, enabling Member States to design and establish their national quantum communication networks, with a total budget of EUR 227 million, of which EUR 114 million is provided by DEP.
- A coordination and support action, PETRUS, which serves as a liaison between all projects, facilitating collaboration, receiving EUR 2 million in funding from DEP.
- A 4-year project, NOSTRADAMUS, started in 2024 with EUR 16 million funding, aimed at establishing a comprehensive testing and evaluation infrastructure for QKD-based technologies and services, to be hosted in future by the Commission's Joint Research Centre (JRC) in Ispra, Italy. JRC is now working closely with NOSTRADAMUS to prepare for this and has conducted functional testing of commercial QKD devices exploiting the fibre network on the campus. Moreover a quantum connection between the JRC Ispra site and the Italian metrological institute "Istituto Nazionale di Ricerca Metrologica" (INRiM) is under deployment as part of the Italian Quantum Backbone.

On July 15, 2025, under the EuroQCI initiative, three new calls for projects were launched, with a total budget of EUR 36 million, on the following topics: maturing of a European industrial ecosystem for security-certified terrestrial QKD technologies and systems; standardisation support for the EuroQCI; coordinated deployment for the EuroQCI.[37]

The Quantum Europe Strategy plans that cross-border terrestrial links and ground stations for satellite links will be deployed during 2025-30. Proposals for cross-border links financed under the CEF have been evaluated, results are expected to be published shortly. The Strategy further plans to support the development, maturation and deployment of quantum communications and facilitate market uptake and security certification. A pilot facility for the European Quantum Internet will be launched in 2026.

35 EuroQCI website at: https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci

36 IRIS²: the new EU secure satellite constellation, available at: https://defence-industry-space.ec.europa.eu/eu-space/iris2-secure-connectivity_en

37 See the calls for proposal available at: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/calls-for-proposals?callIdentifier=DIGITAL-IRIS2-2025-QCI&isExactMatch=true&status=31094501,31094502,31094503&order=DESC&pageNumber=1&pageSize=50&sort By=startDate

2.4 European High Performance Computing Joint Undertaking

The European High Performance Computing Joint Undertaking (EuroHPC JU)[38] is a collaborative initiative between the European Union (EU), its Member States, and private companies. Established in 2018, it aims to develop a world-class supercomputing ecosystem in Europe. The EuroHPC JU has a budget of approximately EUR 7 billion for the period 2021-2027.[39] EUR 3 billion comes from the EU's Multiannual Financial Framework (MFF) 2021-2027 (EUR 1.9 billion from the Digital Europe Programme, EUR 900 million from Horizon Europe, and EUR 200 million from the Connecting Europe Facility-2). The EU's contribution is matched by a similar amount from the participating countries. Private members are also contributing EUR 900 million.

Among the launched projects, there are eight quantum computers and other initiatives in the area of quantum technologies[40]. In 2023, the EuroHPC JU selected six sites across Europe to host and operate cutting-edge EuroHPC quantum computers[41]. The selected hosting entities will operate a diverse range of quantum technologies and architectures on behalf of the EuroHPC JU, making them available primarily for R&D purposes to a broad range of European users, including the scientific community, industry, and the public sector, regardless of their location within Europe. In 2024 (Germany, France, Czechia, Poland) and 2025 (Italy, Spain), the EuroHPC JU announced the signatures of procurement contracts for the following quantum computers at these sites:

- EuroQCS-Italy[42]: 140 qubits, EUR 13 million
- Euro-Q-Exa in Germany[43]: 54 qubits (system 1) and 150 qubits (system 2), EUR 25 million
- Lucy in France[44]: 12 qubits, EUR 8.5 million
- VLQ in Czechia[45]: 24 qubits, EUR 5 million
- Piast-Q in Poland[46]: 20 qubits, EUR 12.28 million
- EuroQCS-Spain[47]: 10 qubits, EUR 8.5 million.

The installation of these systems has begun in 2025. The quantum computers will be co-funded, with 50% of the costs covered by the EuroHPC JU budget, which is part of DEP, and the remaining 50% contributed by the relevant participating states. Additionally, in 2024, the EuroHPC JU selected and signed hosting agreements with two new sites to host and operate state-of-the-art quantum computers, in Luxembourg and the Netherlands, further expanding Europe's quantum computing capabilities. The Quantum Europe Strategy plans to expand the capacity of EuroHPC JU quantum computing systems from 2026 and to set up a monitoring framework for quantum computing.

38 EuroHPC JU website, available at: https://eurohpc-ju.europa.eu/index_en

39 See EuroHPC JU webpage on EC website at: https://digital-strategy.ec.europa.eu/en/policies/high-performance-computing-joint-undertaking

40 Overall description of quantum computers of EuroHPC JU at: https://eurohpc-ju.europa.eu/eurohpc-quantum-computers/our-quantum-computers_en

41 Agreement signature for the six hosting sites at: https://eurohpc-ju.europa.eu/one-step-closer-european-quantum-computing-eurohpc-ju-signs-hosting-agreements-six-quantum-computers-2023-06-27_en

42 EuroQCS-Italy, available at: https://eurohpc-ju.europa.eu/signature-procurement-contract-eurohpc-quantum-computer-located-italy-2025-03-27_en

43 Euro-Q-EXA available at: https://eurohpc-ju.europa.eu/signature-procurement-contract-eurohpc-quantum-computer-located-germany-2024-10-15_en

44 Lucy, available at: https://eurohpc-ju.europa.eu/signature-procurement-contract-lucy-new-eurohpc-quantum-computer-located-france-2024-09-26_en

45 LUMI-Q consortium, available at: https://eurohpc-ju.europa.eu/advancing-european-quantum-computing-signature-procurement-contract-eurohpc-quantum-computer-located-2024-09-26_en

46 EuroQCS-Poland project, available at: https://eurohpc-ju.europa.eu/advancing-european-quantum-computing-signature-procurement-contract-euroqcs-poland-2024-07-10_en

47 See MareNostrum Ona quantum computer, available at: https://eurohpc-ju.europa.eu/signature-procurement-contract-eurohpc-quantum-computer-located-spain-2025-01-28_en

In addition, the HPCQS project (2021-2025) aims to integrate two quantum simulators into two existing supercomputers:

- JADE in Germany: 100 qubits,
- Ruby in France: 100 qubits.

The project has received funding of EUR 12 million, again 50% Horizon Europe, 50% Member States.

2.5 Chips Joint Undertaking (Chips JU)

The EU Chips Act[48] is an EU Regulation approved in 2023, aiming to strengthen the EU semiconductor industry and reduce its dependence on foreign suppliers. Pillar I of the Chips Act aims to support technological capacity building and innovation by bridging the gap between advanced research and industrial exploitation[49]. In this respect, quantum chips are included as the upcoming technological innovation and the construction of pilot lines for quantum chips is seen as a first step towards the future goal. The **Chips for Europe Initiative** established by Pillar I has the operational objective 3 on "building advanced technology and engineering capacities for accelerating the innovative development of cutting-edge quantum chips and associated semiconductor technologies" Specifically it aims to: "*(i) develop innovative design libraries for quantum chips; (ii) support the development of new or existing pilot lines, clean rooms and foundries for prototyping and producing; quantum chips for the integration of quantum circuits and control electronics; (iii) develop facilities for testing and validating advanced quantum chips produced by the pilot lines, with a view to closing the innovation feedback loop between designers, producers and users of quantum components*". The relevance of quantum chips has been stressed also in the Draghi report, which suggested the launch of a long- term EU Quantum Chips plan. The objective is not only to ensure the investment in this highly innovative and potentially disruptive sector, but also to coordinate and concentrate the funding, avoiding the duplication of investments and architectural choices.

The primary implementation of the Initiative is entrusted to the **Chips Joint Undertaking (JU)**[50] established by Council Regulation (EU) 2021/2085. The Chips JU is a public-private partnership be- tween EU and the semiconductor industry, aimed at supporting research, development, and innovation in the field of microelectronics and nanoelectronics. The Chips JU is the successor of the Key Digital Technologies Joint Undertaking (KDT JU) which, in turn, is the successor to the Electronic Components and Systems for European Leadership (ECSEL) JU The Chips JU funds research and innovation projects co-financed by the European Commission through Horizon Europe. The Chips JU[51] is already support- ing important projects on quantum technologies. Among them, it is worth mentioning the ARCTIC project[52] on cryogenic technologies for larger-scale quantum systems. Moreover, in September 2024, the Chips JU launched a call to select projects for the development and manufacturing-of quantum technologies, in order to establish a manufacturing supply chain for quantum chips in Europe. EU funding for this call is of EUR 65 million, and a similar amount is expected to be provided by the participating states of the Chips JU. Other calls will follow, this investment is part of the EU's overall commitment to invest EUR 200 million in quantum chips through the Chips JU over the next three years.[53] The Quantum Europe Strategy further states that the Commission will release a Quantum Chips Industrialisation Roadmap within 2026.

48 Regulation (EU) 2023/1781 of the European Parliament and of the Council of 13 September 2023 establishing a framework of measures for strengthening Europe's semiconductor ecosystem and amending Regulation (EU) 2021/694 ("Chips Act") https://eur-lex.europa.eu/eli/reg/2023/1781/oj/eng

49 European Chips Act: The Chips for Europe Initiative, at: https://digital-strategy.ec.europa.eu/en/factpages/european-chips-act-chips-europe-initiative

50 Chips JU website at: https://www.chips-ju.europa.eu/

51 "EU invests EUR 65 million in quantum chips", available at: https://digital-strategy.ec.europa.eu/en/news/eu-invests-eu65-million-quantum-chips

52 Advanced Research on Cryogenic Technologies for Innovative Computing (ARCTIC) https://www.ipms.fraunhofer.de/en/Strategic-Research-Areas/Quantum-Computing/ARCTIC.html

53 More information available at: https://digital-strategy.ec.europa.eu/en/news/eu-invests-eu65-million-quantum-chips

Quantum chips

"Quantum chips" are integrated circuits containing miniaturised components that perform operations at the quantum level. While circuits in modern classical chips may be miniaturised to the extent that there is only a small number of atoms in each component (e.g. gate of the transistor), the design is still mostly based on the same principles as for full-sized devices, for example defined in terms of electrical voltages and currents. Quantum chips, instead, are designed to realise and exploit quantum states, with properties such as superposition and entanglement.

Quantum chips are often photonic integrated circuits (PICs), exploiting particles of light (photons) instead of electrons. Classical PICs also exist but photonics is particularly important for quantum technology. Other types of quantum chip include atom chips, miniature ion-traps and superconducting chips.

While quantum chips based on semiconductors are undoubtedly the first step, the general field of quantum technology requires also non-semiconductor photonic components and superconductors. This is in contrast with the conventional chip industry, which is dominated by semiconductor materials – silicon for electronic chips and different semiconductors and compounds for PICs (e.g., Si, SiN, InP). Attempts are being made to establish a roadmap for quantum chips. Since 2018, the IEEE International Roadmap for Devices and Systems, the successor to the famous International Technology Roadmap for Semiconductors, has included quantum information processing. Quantum is grouped with cryogenic electronics, suggesting an emphasis on low temperature platforms.

Points for debate

- Is quantum appropriately addressed in the existing Chips Act? Should a future quantum chips plan take a different approach?

2.6 Photonics21

Photonics21[54] is a European Technology Platform (ETP) established in 2005 by the European Commission, aiming to promote and develop the field of photonics in Europe. As an ETP[55], it brings together industry, research, and academia to create a unified vision and strategy for the advancement of photonics. The platform focuses on key areas, including photonics for healthcare, energy, communications, and manufacturing. To support the industry, Photonics21 has backed several projects partially funded by the European Commission through the Horizon 2020 and now Horizon Europe framework. Some of these projects have high relevance to quantum technologies, in particular for quantum chips which can be built using photonic integrated circuits (PICs). We found at least 9 Photonics21 projects important for the development of quantum technologies, although most are still related to "classical" photonic applications (see Section 3.1). Notable projects funded under the Photonics21 technology platform include: PIX4life[56], promoting silicon nitride (SiN) PIC technology for health applications; PIXAPP[57] on open-access PIC assembly and packaging pilot line; and the JePPIX[58] manufacturing pilot line for indium phosphide (InP) PICs. PICs have achieved a good level of maturity in some sectors (e.g., applications in data centre as transceivers) and can become a viable option for realizing the future class of quantum chips.

While some technological challenges of photonic integration are common to photonic applications (e.g., hybrid/het-

54 Photonics21 website at: https://www.photonics21.org/

55 European Technology Platforms (ETP) are public-private partnership established in the research field at European level. These are industry-led stakeholder associations to define and implement a strategic research agenda (SRA) aiming at aligning research priorities in a technological area. https://www.europarl.europa.eu/RegData/etudes/ATAG/2017/603935/EPRS_ATA(2017)603935_EN.pdf

56 PIX4LIFE webpage at: https://www.photonics21.org/ppp-projects/past-projects/workgroup-7/Pix4life.php

57 PIXAPP website at: https://pixapp.eu/

58 JePPIX pilot line is enabled by InPulse project, see at: https://www.photonics21.org/ppp-projects/past-projects/workgroup-6/Inpulse.php

erogenous integration of platforms, packaging), quantum applications introduce new technological obstacles such as the need for the components to operate at cryogenic temperatures, the need for integrated detectors at various wavelength ranges (e.g., for quantum sensing), novel types of substrates (e.g., diamond and 2D materials). A more detailed overview of the technological challenges for quantum integration is presented in Photonics21 position paper[59].

Points for debate

- Are the requirements of the photonics industry aligned with the requirements of the emerging quantum industry?
- Is the quantum community adequately represented in Photonics21?

2.7 European Association of National Metrology Institutes (EURAMET)

EURAMET[60], the European Association of National Metrology Institutes, serves as a coordinating body for National Metrology Institutes (NMIs) and Designated Institutes (DIs) in Europe. Its primary objectives include facilitating the cooperation in metrology research, ensuring the traceability of measurements to the International System of Units (SI), and promoting international recognition of national measurement standards and related Calibration and Measurement Capabilities (CMC). Within EURAMET, the European Metrology Network (EMN) for Quantum Technologies[61] coordinates European measurement science research in the field of quantum technologies.

EURAMET has launched several research projects under its European Metrology Research Programmes (EMRP and EMPIR), focusing on Quantum Metrology in three key areas: quantum clocks, quantum electronics, and quantum photonics. Since 2010, EURAMET has supported more than 30 projects in quantum technologies, with partial funding provided by the European Union through the Horizon 2020 and Horizon Europe frameworks.

Points for debate

- Quantum for metrology versus metrology for quantum: What is the correct balance between funding quantum technology as a tool in metrology and funding metrology techniques for evaluating quantum devices?

2.8 European Innovation Council (EIC)

The European Innovation Council (EIC)[62] is an EU body for funding innovative companies, especially startups and small and medium-sized enterprises SMEs, through grants and investments. The EIC's strategy and implementation are guided by the EIC Board, whose independent members are appointed from the world of innovation. The EIC's activities are managed by the European Innovation Council and SMEs Executive Agency (EISMEA)[63], which is responsible for overseeing the Commission initiatives related to SMEs. EIC's projects receive financial support from the European Union through the Horizon programmes, EIC being a key component of Horizon Europe's Pillar III – Innovative Europe.

59 Photonics21, "Quantum PIC position paper", https://www.photonics21.org/2022/position-paper-on-quantum-pics-available-for-download-now%21

60 EURAMET website at: https://www.euramet.org/

61 Webpage of the European Metrology Network for Quantum Technologies at: https://www.euramet.org/european-metrology-networks/quantum-technologies

62 EiC website at: https://eic.ec.europa.eu/about-european-innovation-council_en

63 EISMEA website at. https://eismea.ec.europa.eu/index_en

The EIC pilot phase was launched in 2018, incorporating existing instruments under the Horizon 2020 programme, in particular the SME instrument and Future & Emerging Technology (FET) programme. The FET programme focused on developing groundbreaking new technologies by exploring novel and high-risk ideas building on scientific foundations. Initially, the EIC provided grants under the 2018- 2020 Horizon 2020 programme, specifically under the call for Industrial Leadership - Innovation in SMEs. Since 2021, the EIC has financed three main project categories, under Horizon Europe: Pathfinder, Transition, and Accelerator. Pathfinder projects support the early development of breakthrough technologies up to proof of concept (TRL 1-4) with grants of up to EUR 4 million. Transition projects validate and demonstrate the application of technology in a relevant environment, developing business and market readiness (TRL 5-6) with grants of up to EUR 2.5 million. Accelerator projects support the scale-up and commercialisation of innovative projects (TRL 6-8) to be completed within 24 months, with grant contribution of up to EUR 2.5 million. In addition to the grant, the EIC Accelerator can provide an equity investment through the EIC Fund,[64] from EUR 0.5 million to EUR 10 million.

The Pathfinder projects are typically Horizon projects, focusing on research and led by consortia of universities and research institutions with limited company participation. The EIC Transition and Accelerator projects (as well as those that were funded by EIC under the Horizon 2020 programme) are conceived as a different type of European projects. These projects are usually awarded to a single entity, such as a startup or SME, with the primary objective of providing financial support to young and innovative companies for developing technologies up to commercial applications.

The EIC has a dedicated internal programme for quantum with a manager experienced in the sector. Its importance has also been highlighted by the horizon scanning exercise, conducted by EIC in collaboration with the JRC last year [38]. According to our analysis (see Section 3.1), between 2014 and 2024, more than 100 projects were funded on quantum technologies, including those funded through the FET initiative, allocating approximately EUR 300 million in EU funds. While the number of projects is high, each received only a few million euros. However, achieving the scheme's ambitious goals with low project budgets and short timeframes appears to be challenging. It can be over-optimistic, or even completely unrealistic, to hope to bring a new quantum application from low to high technology readiness in a few years on just a few million euros funding. An example is the Prometheus project[65] (2020-2022), in which the Finnish startup IQM received EUR 2.5 million for a two-year project with the stated aim that it would lead to a 1000 qubit machine in 5 years. Their current largest commercial quantum computer offers 150 high fidelity qubits, and that is good by industry standards. More achievable scientific and business goals could be set, without compromising the primary purpose of the EIC funding, i.e. fostering the growth of the quantum SME sector through publicly funded capital investment.

Recently, the EIC announced the 40 start-ups that secured EIC support in the latest round of the EIC Accelerator.[66] They include quantum technology companies such as: Groove Quantum (Netherlands); Q* BIRD (Netherlands); and Quantum Dice Limited (UK). In addition, the EIC also operates the STEP Scale Up scheme, part of the Strategic Technologies for Europe Platform (STEP). This scheme, managed by the EIC Fund, provides financial support in the form of investments to startups, small and medium-sized enterprises (SMEs), and small mid-caps, with funding ranging from EUR 10 million to EUR 30 million. The focus is on Europe's strategic technology sectors, including quantum technologies. In April 2025[67] and June 2025[68] the Commission announced the first and second groups of companies that have successfully passed the evaluation phase of the STEP Scale Up call. Those companies include the quantum technology companies: Pasqal (France), IQM Finland (Finland), Multiverse Computing (Spain) and Classiq technologies (Israel).

64 The EIC Fund is the Venture Capital investment arm of EIC; it is financed by the European Commission with the investment advice of the EIB: https://eic.ec.europa.eu/eic-fund_en

65 CORDIS page of Prometheus project: https://cordis.europa.eu/project/id/959521

66 See EiC news on 30 June 2025 https://eic.ec.europa.eu/news/health-space-40-start-ups-secure-eic-support-latest-round-eic-accelerator-2025-06-30_en

67 See EiC news on 3 April 2025 at: https://eic.ec.europa.eu/news/first-companies-put-forward-major-investments-under-eic-step-scale-scheme-2025-04-03_en

68 See EiC news on 12 June 2025 at: https://eic.ec.europa.eu/news/new-companies-put-forward-major-investments-under-eic-step-scale-scheme-2025-06-12_en

The Quantum Europe Strategy points out that EIC funds incudes the Scaleup Europe Fund, to mobilise private funds and investment in strategic sectors such as quantum.

Points for debate

- The EIC has financed numerous projects, but each receives limited funding. Is this approach sufficient to fulfil its ambitious goals, or would it be more effective to finance fewer projects with larger investments?

2.9 European Investment Bank (EIB)

The European Investment Bank (EIB)[69] has highlighted the importance of quantum technologies, acknowledging their potential to drive innovation and transform various sectors of the economy. To accelerate progress and maintain Europe's competitiveness in the global quantum landscape, the EIB has emphasised the need for substantial investment. In this context, under the InvestEU programme, the EIB has launched a EUR 500 million thematic venture debt facility for key enabling technologies, including quantum technologies, providing investment up to EUR 50 million. In 2021, IQM Quantum Computers of Finland, a European leader in building quantum processors, has received EUR 35 million from the EIB to accelerate the development of Europe's first quantum-dedicated fabrication facilities in Espoo, Finland.[70] However, the EIB has noted that the scope of this thematic venture debt facility is broad, encompassing several areas. As a result, there is the risk that quantum technologies may not receive the attention they require under this facility.[71]

2.10 European Defence Fund (EDF)

The EDF[72] is an EU programme to support the development of defence capabilities and technologies in Europe. With a budget of EUR 7.9 billion for the period 2021-2027, the EDF provides funding for research and development projects, as well as capability development initiatives. The fund is managed by the European Commission in collaboration with the European Defence Agency (EDA) and EU Member States. It provides financial assistance through grants that can cover up to 100% of eligible costs. Regarding quantum technologies, the EDF has identified them as a key area of interest due to their potential to significantly impact the defence and security sector. As a result, the EDF has financed several projects in this field. Under the Preparatory Action on Defence Research, the precursor programme to the EDF, the QuantaQuest project[73] on Quantum Secure Communication and Navigation for Europe received EUR 1.5 million in funding. In the 2021 call, three projects were found under the EDF (ADEQUADE[74], Q-SiNG[75], and SMiEQ[76]), and an additional project (Optimas[77]) was financed in the 2023 call, focusing on quantum sensing, quantum random number generation, and quantum communication.

In April 2025, the results of the 2024 call were published, which include several projects on quantum technologies. Those include three projects under the topic "Disruptive Technologies – Quantum": ORQESTRAS[78] focusing on PQC; Q-ARM[79] on quantum-secure communication; and SQORPION[80] on quantum sensors. Additionally, the call funded QANCOMFIN[81], to design classical and quantum algorithms, and NEUROQUAD[82], which aims at combining neurotechnology, AI, and quantum computing to enhance cognitive abilities. To date, the Commission has allocated more than EUR 80 million to fund EDF projects on quantum technologies (see Section 3.1).[83] Security and defence aspects are discussed in detail in the Quantum Europe Strategy, which explains the context within broader EU defence and security policy and cooperation with NATO. It plans that the Commission will develop a Quantum Sensing Space and Defence Technology Roadmap by 2026 and contribute to the European Armament Technological Roadmap in 2025. "Spin-in" initiatives will be launched for civil companies and academia to work on defence applications.

2.11 European Research Council (ERC) and Marie Skłodowska-Curie Actions (MSCA) fellowships

Beyond specific large-scale initiatives, the Commission is supporting quantum research, especially its foundational aspects, through funding schemes like ERC[84] grants and MSCA[85] fellowships, which are key components of the Horizon Europe's Pillar I – Excellent Science. Numerous projects related to all areas of quantum technologies, including some projects in PQC, have been financed under these programs, in particular in the field of quantum physics. The research in quantum science and its theoretical and experimental aspects is essential for promoting innovation, tackling the future technological advancements in the field and creating a highly-skilled workforce. Our analysis (see Section 3.1) reveals that between 2014 and 2024, the ERC funded over 200 projects relevant to quantum technologies, for about EUR 500 million. During the same period, MSCA funded about 300 projects, with a total investment of around EUR 150 million. This indicates that the EU is making significant investments in fundamental research related to quantum technologies.

2.12 European Cooperation in Science and Technology (COST) Actions

The European Cooperation in Science and Technology (COST)[86] is an international non-profit entity joining together 38 countries. It supports the creation of research networks, called COST Actions. These networks are a platform for collaboration among scientists across Europe and beyond.

69 EIB website at: https://www.eib.org/en/

70 See IQM quantum computing on EIB website at: https://www.eib.org/en/projects/all/20210429

71 See European Investment Bank, "A quantum leap in finance – How to boost Europe's quantum technology industry," European Investment Bank, 2024, available at: https://www.eib.org/en/publications/20220112-a-quantum-leap-in-finance-executive-summary

72 European Defence Fund website at: https://defence-industry-space.ec.europa.eu/eu-defence-industry/european-defence-fund-edf-official-webpage-european-commission_en

73 EDA news on "QuantaQuest project explores application of quantum technologies in defence," 19 January 2024, available at: https://eda.europa.eu/news-and-events/news/2024/01/19/quantaquest-project-explores-application-of-quantum-technologies-in-defence

74 ADEQUADE factsheet, available at: https://defence-industry-space.ec.europa.eu/system/files/2022-07/Factsheet_EDF21_ADEQUADE.pdf

75 Q-SING factsheet, available at: https://defence-industry-space.ec.europa.eu/document/download/e97930f9-db47-4d05-b6a8-7ff639efef98_en?filename=Factsheet_EDF21_Q-SiNG.pdf&prefLang=nl

76 SMiEQ factsheet, available at: https://defence-industry-space.ec.europa.eu/document/download/40839282-e025-4822-890a-712a5d77681c_en?filename=Factsheet_EDF21_SMiEQ.pdf&prefLang=lt

77 OPTIMAS factsheet, available at: https://defence-industry-space.ec.europa.eu/document/download/ffafa5ba-3412-482a-aa1f-7a21fec7e7af_en?filename=EDF-2023-DA-C4ISR-LCOM%20OPTIMAS.pdf

78 ORQESTRA factsheet, available at: https://defence-industry-space.ec.europa.eu/document/download/5a308169-efa7-498f-a090-78fbb26e3adc_en?filename=FACTSHEET_EDF_2024_LS_RA_DIS_QUANT_STEP_101224573_ORQESTRA.pdf

79 Q_ARM factsheet, available at: https://defence-industry-space.ec.europa.eu/document/download/c421855b-0df4-4a57-abd2-4598a842ff80_en?filename=FACTSHEET_EDF_2024_LS_RA_DIS_QUANT_STEP_101224135_Q_ARM.pdf

80 SQORPION factsheet, available at: https://defence-industry-space.ec.europa.eu/document/download/87e7f6e6-d61e-4291-a900-bb28285f1bd4_en?filename=FACTSHEET_EDF_2024_LS_RA_DIS_QUANT_STEP_101224744_SQORPION.pdf

81 QANCOMFIN factsheet available at: https://defence-industry-space.ec.europa.eu/document/download/c9b28e12-9ee5-4770-9c8d-996be325ef3c_en?filename=FACTSHEET_EDF_2024_LS_RA_SMERO_NT_101224229_QANCOMFIN.pdf

82 NEUROQUAD factsheet, available at: https://defence-industry-space.ec.europa.eu/document/download/08cc3dee-a4a1-48de-80d4-cd97f122babe_en?filename=FACTSHEET_EDF_2024_LS_RA_DIS_NT_101224494_NEUROQUAD.pdf

83 Note that the data in Section 3.1 does not include projects from the 2024 calls, as their funding was not allocated by 2024

84 ERC website at: https://erc.europa.eu/homepage

85 MSCA website at: https://marie-sklodowska-curie-actions.ec.europa.eu/actions/postdoctoral-fellowships

86 COST website at: https://www.cost.eu/

COST is funded by the European Commission Horizon budget. Typically, a COST Action lasts four years and receives EUR 125 000 in its first year, followed by an average of EUR 150 000 per year for another three years. This funding is not meant to cover research but networking activities like events, scientific missions, training schools, communication activities. Over the years, COST has funded several networks relevant for quantum technologies, including on: Trapped Ions (TIPICQA),[87] Quantum Technologies with Ultra-Cold Atoms (AtomQTech),[88] Quantum Technologies in Space (QTSpace),[89] Machine Learning and Quantum Computing for Future Colliders (MLQC4FC),[90] and Superconducting Quantum Technologies (NANOCOHYBRI).[91]

2.13 European Space Agency (ESA)

The **European Space Agency (ESA)** started exploring the use of quantum technologies in the early 2000s. ESA's involvement in quantum covers all sectors: quantum communication and cryptography, quantum sensing and quantum computing and simulation. On quantum communication, ESA is collaborating with the European Commission in the development of **EuroQCI's Space Segment** for the distribution of quantum cryptographic keys from satellite. In its first phase, ESA is working with SES SA of Luxembourg on a co-financed project to launch a demonstration satellite, **Eagle1** for testing a phase-encoded BB84 QKD protocol in low Earth orbit. Launch is currently foreseen for August 2026. Lessons learned from Eagle-1 will guide the development of the next EuroQCI mission (in cooperation with the European Commission), **SAGA** (Security And cryptoGrAphic mission[92]), envisioning two stages, SAGA1 and SAGA2. SAGA1 will develop satellite-based quantum keys for a Europe-wide service based on BB84 with polarisation encoding. The system should include key management, secure symmetric encryption on classical channels. The second stage, SAGA2 will move on to develop entanglement-based services, possibly including quantum repeaters, towards the development of a quantum internet network.

Optical ground stations for EuroQCI Space Segment are being deployed under the CEF call for cross- country links. SAGA is part of ScyLight, ESA`s strategic programme "Space for Optical & Quantum Communications", which is supporting the development of disruptive technologies, in cooperation with industry and academia. In quantum sensing, ESA developed a quantum magnetometer, MAGSCA, for the JUICE spacecraft, based on quantum interferometry and on the Zeeman effect to detect the magnetic field around Ganymede. ESA is also planning the use of highly precise atomic clocks for positioning navigation and timing through the ACES experiment as part of the International Space Station payload by 2025. Finally, the QC4EO study applied quantum computation models to process Earth observation data. ESA's Advanced Concept Team is currently exploring the use of Noisy Intermediate-Scale Quantum (NISQ) Ising machines for different space applications.

Since 2021, ESA's quantum technology activities are coordinated via the **Quantum Technology Cross-Cutting Initiative** (QT-CCI)[93] through a wide consultive process, in coordination with industry and research entities, bridging different programmes and partnerships. Implemented and lead by the TEC-MME core group, the initiative involves over 60 ESA colleagues working in 10 directorates and over 100 active collaborations. QT-CCI activities include: development of atomic frequency standards and cold atom interferometers; testing decoherence at the quantum gravity limit; using quantum computing algorithms for Earth observation data and orbit optimisation; exploiting QKD, QRNG and PQC in quantum satellite communication; exploiting advanced quantum sensing techniques in space probing.

The total budget spent and committed in quantum amounts to EUR 182.3 million, excluding ESA mission projects. Of this budget, the largest share is invested in quantum communications (69%), followed by atom interferometry and atomic frequency standards (8%, 11%) and by PQC (5%).

In addition to the investments in R&D activities, several missions using quantum technologies were financed with more than EUR 300 million of ESA's budget (excluding significant additional contributions from national budgets and from industry investments): MAGSCA (payload aboard JUICE), ACES, EAGLE-1, QKDSat, OPS-SAT VOLT.

The Quantum Europe Strategy plans roadmap for space-related activities, to be jointly developed with ESA.

Quantum space communications

Pioneering experiments demonstrating the feasibility of single photon exchange with a low-Earth orbit satellite were conducted by Paolo Villoresi (University of Padova) and colleagues in the early 2000's. from the Matera Laser Ranging Facility [40]. The Chinese Academy of Sciences were the first to demonstrate a fully-functioning QKD satellite, Micius, part of the QUESS (Quantum Experiments at Space Scale) programme [41], [42], [43], coordinated by Pan Jianwei (University of Science and Technology of China). The satellite, running from 2017, was involved in a series of quantum demonstrations, ranging from QKD to entanglement distribution and teleportation. The mission was followed by the launch of Jinan-1, a quantum mini-satellite (about 100 kg) intended as the first of a QKD constellation and with the capacity to generate keys one hundred times faster while cutting costs by about 45 times [28]. China is currently the only country with an operational multi-node quantum satellite network, while Europe, USA and Canada are still in the planning and testing phases for space quantum communications, with actual ongoing projects in quantum sensing and quantum computing.

Upon receiving the news of Micius' successful QKD mission, in 2017 NASA defined it 'a new Sputnik moment' and reacted launching its own quantum agenda. In 2024, NASA initiated the Space Entanglement and Annealing QUantum Experiment (SEAQUE, coordinated by Paul Kwiat, University of Illinois), to test entanglement distribution towards enabling quantum connected nodes in space.[94] The QTech (Quantum Technologies) project, a partnership of Glenn and NASA's Ames Research Center, along with the Air Force Research Laboratory and IJK Controls LLC, is attempting to harness the power of quantum technologies to ensure communication availability and address potential cybersecurity challenges.

2.14 Other projects

There are a few quantum technology projects that received funding through other EU instruments. For example, the Smart Networks and Services Joint Undertaking (SNS JU) funded projects on quantum communication and PQC, via the Horizon Europe programme, including CONFIDENTIAL6G[95] and XTRUST-6G,[96] which are focused on the development of 5G and 6G networks. Also, the European Union's Cybersecurity Competence Centre founded the project PQC4eMRTD,[97] PQCSA[98] and PiQASO[99] on PQC, through the Digital Europe Programme.

87 Webpage of TIPICQA COST actions at https://www.cost.eu/actions/CA17113/

88 Webpage of AtomQTech COST action at: https://www.cost.eu/actions/CA16221/

89 Webpage of QTSpace COST action at: https://www.cost.eu/actions/CA15220/

90 Webpage of MLQC4FC COST actions at: https://www.cost.eu/actions/CA24146/

91 Webpage of NANOCOHYBRI COST actions: https://www.cost.eu/actions/CA16218/

92 ESA - SAGA for quantum key distribution, available at: https://www.esa.int/ESA_Multimedia/Images/2019/04/SAGA_for_quantum_key_distribution

93 ESA Quantum Technologies webpage, at: https://activities.esa.int/cluster/918

94 Kwiat Quantum Information Group: SEAQUE website: https://research.physics.illinois.edu/QI/Photonics/SEAQUE/

95 Project website: https://confidential6g.eu/

96 Project website: https://xtrust-6g.eu/

97 Project website: https://www.pqc4emrtd-project.eu/

98 Project website: https://pqcsa.eu/

99 Project website: https://www.piqasoproject.eu/

3 Economic and financial landscape and scientific output

3.1 EU public funding of quantum technologies in 2014-2024

In this section we analyse the trends in EU public funding of quantum technologies, including quantum computing, quantum communication, quantum sensing and PQC projects.[100] Our analysis is limited to EU funding[101] and does not include projects cofinanced with ESA.[102] To this end, we built a database of quantum technology projects funded by the EU, starting from a database[103] at the European Commission's Directorate-General for Communications Networks, Content and Technology Accessibility (DG CNECT). It employs an AI-driven selection algorithm to identify projects from CORDIS[104] and the EU Funding & Tenders Portal.[105] We further refined this dataset by addressing false positives and missing entries through keyword analysis and manual verification.

The EU funds a wide array of quantum technology projects, ranging from fundamental science to initiatives explicitly aimed at commercial product development. This diversity prompted us to define rigorous selection criteria to establish whether a funded project belongs or not to a specific quantum technology domain, or if it is a general quantum physics project. Indeed, while many projects are explicitly on quantum technologies—such as those under the Quantum Flagship initiative—others are less straightforward, particularly those financed under the ERC and MSCA. These projects, in fact, often are at a low TRL and deal with topics closer to the foundations of quantum mechanics, cosmology and quantum gravity or materials research (including superconductivity, superfluidity, graphene and semiconductors). While innovation in all these topics could potentially influence quantum technology development in the long term, many of them remain in the realm of pure scientific inquiry and with limited short or medium-term practical applications. Of these projects, we accounted for only those with a direct near-future relevance for quantum technology, disregarding those with too loose implications for technology. We acknowledge that this approach is inherently conservative and involves subjective judgment based on project analysis. Moreover, the automated content selection of the DG CNECT database, which relies on AI-driven tools, is subject to the inherent limitations common to all AI systems. However, we believe that our dataset provides a robust estimation of EU-funded quantum technology projects, and, to the best of our knowledge, it represents the most precise compilation currently available.

We categorised projects into two main groups: **fundamental science** and **specialised areas**. This classification was based on the project description. Projects were categorised as fundamental science, if their core mission was to elucidate phenomena with an application in quantum technology, without detailing an actual implementation. Projects not designated as fundamental science were then labelled into four technology areas: **quantum computing,**[106] **quantum sensing, quantum communication,**[107] and **PQC**. Projects covering multiple technologies were assigned multiple labels accordingly. The projects on quantum chips have been classified under quantum communication, sensing or computing in relation to design specifiers and main applications.

Table 1 presents an overview of EU funds on quantum projects allocated under various EU initiatives between 2014 and 2024. The data presented includes: the number of funded projects, the total cost of those projects, the total EU funds allocated to those projects, the average EU funding per project, and the percentage of the total project cost

100 The reason for including PQC in accounting for quantum technology patents, companies and public funding is twofold: on one hand, even though PQC does not itself make use of quantum technologies nor of quantum theoretical tools, it is anyway intended to counter quantum computers' codebreaking algorithms; on the other, the majority of reports on quantum cited in this report included PQC among quantum communication technologies and therefore it seemed as a straightforward comparison. We should also add that several companies in the field usually offer, besides PQC, also QKD or products based on quantum algorithms, and therefore can be classified as quantum companies at full scale.

101 For the EIC, we considered the EU grants and not the equity investments from the EIC Fund. We also do not consider the investments of the EIB as those are venture debt.

102 See Section 2.13 for information on the ESA activities on quantum technologies.

103 The database and search tool, based on a LLM AI algorithm, was developed by DG CNECT under a limited time frame project.

104 CORDIS website at: https://cordis.europa.eu/

105 EU Funding & Tenders Portal, https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/home

106 Quantum repeaters and quantum memories, which are essential for the development of entanglement-based networks and quantum internet, are grouped under quantum computing.

107 The field of quantum communication includes QKD, quantum protocols, and quantum network design.

covered by the EU contributions. presents the EU funds allocated to the various quantum technology initiatives for the period 2014-2024, while presents the annual allocation from 2014 to 2024 (COST Action data are too small to appear in this figure). The annual allocation is based on the contract signature data.[108] For instance, if a project contract was signed in 2022, we attributed its entire funding to 2022, even if the project spans multiple years and the funds are spent progressively over its duration. The cost of the project, as well as the EU contribution, are those reported in the CORDIS database or EU Funding & Tenders Portal. For the projects not listed in these datasets, the information is collected from the individual project websites or the funding initiatives' websites.[109]

Table 1 EU funds allocated to quantum projects for various EU initiatives in 2014-2024 (does not include ESA projects).

EU initiatives	Number of projects	Total cost	EU funds (m EUR)	Avg. EU funding per project (m EUR)	% of EU fund over total cost
ERC	244	492	492	2,0	100%
Quantum Flagship	65	476	468	7,2	98%
EIC[110]	117	341	306	2,6	90%
EuroQCI	34	293	162	4,8	55%
MSCA	293	152	142	0,5	94%
EURAMET	36	-	62	1,7	-
Photonics21	9	62	57	6,3	91%
EDF	5	58	53	10,6	91%
Chip JU	5	164	51	10,2	31%
EuroHPC6	77	36	5,9	46%	
QuantERA	101	117	27	0,3	23%
COST Action	6	4	4	0,7	100%
Other Horizon projects	34	153	147	4,3	96%
Other non- Horizon projects	9	50	32	3,6	64%
Total	**964**	**2439**	**2038**	**2,1**	**84%**

Source: JRC elaboration

We identify almost **1000 projects on quantum technologies receiving a total of about EUR 2 billion** from EU funds. Approximately 95% of these projects were funded, or co-founded, through the Horizon 2020 and Horizon Europe frameworks which covered about 70% of the sum of overall budget of all projects. This makes the Horizon programmes, by far, the most significant sources of support for quantum technology in the EU. The primary initiative in terms of fund allocated was ERC, which provides funds for research projects mainly to universities and research centres. The ERC is followed by the Quantum Flagship and the EIC, which, together with the ERC, account for over half of all EU funds allocated to quantum projects. The average allocation per fund was EUR 2.1 million per project. Iinitiatives that fund projects closer to commercial applications, such as EuroQCI, the Quantum Flagship, the EDF, and the Chips JU, receive higher average funding than research-oriented projects from the ERC or MSCA or the COST Action, as developing a commercial product is typically more expensive. However, we note that the EIC provides re-

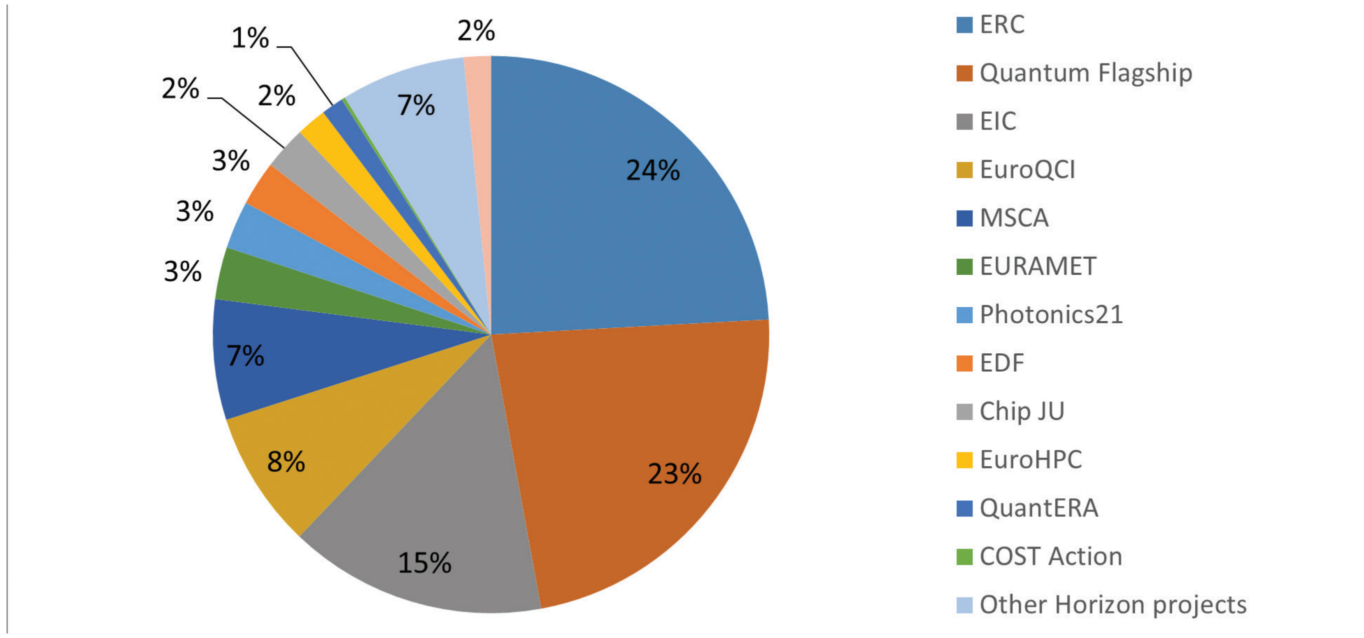
108 Where the projects' contract signature date was unavailable, we used the project start date.

109 This was the case for the QuantERA projects, the COST Action projects and EURAMET projects. For the QuantERA projects, we used the total project costs as reported by the QuantERA Initiatives. For the COST Action projects, as we could not find public cost data for the individual projects, we assumed that each COST Actions project received the maximum available funding. For EURAMET projects, we were able to obtain cost data for a subset of projects, and only for the portions covered by EU funds. For the remaining projects, we assumed that the EU-funded part of the cost was equal to the average EU-funded part from the available project data.

110 The EIC projects also include those financed under the FET programme.

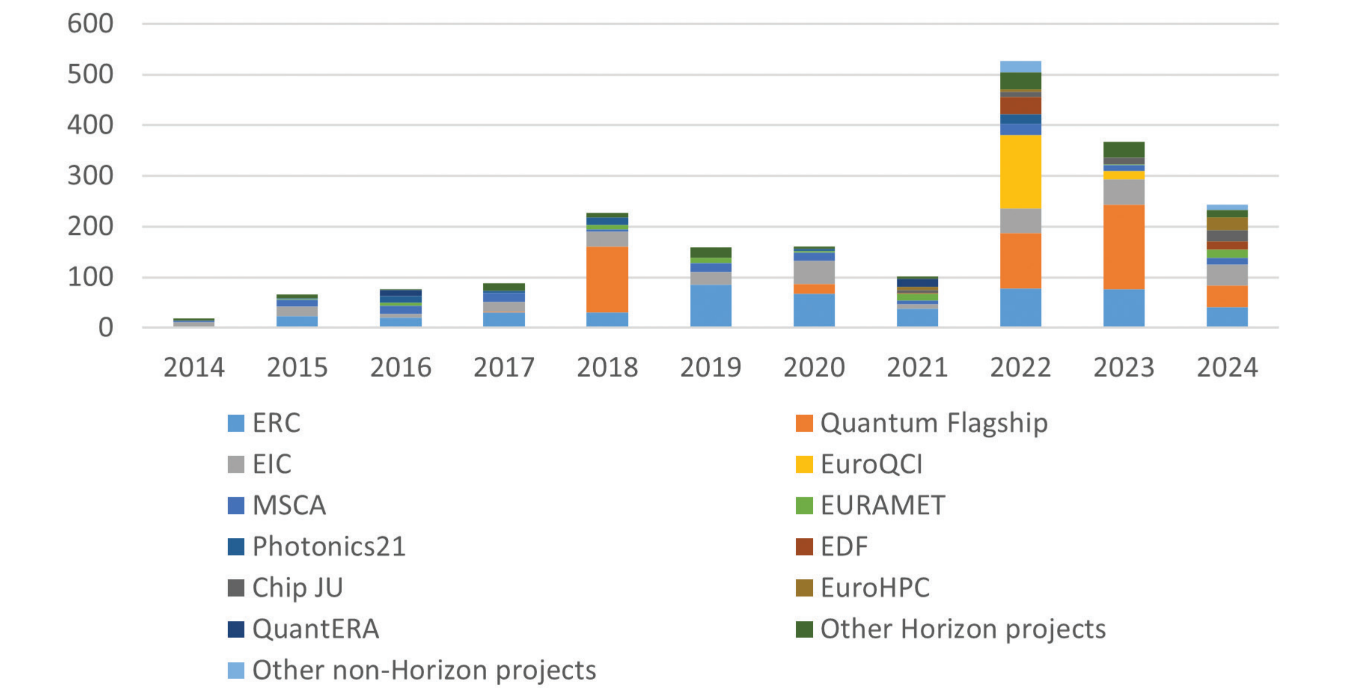
latively low average support with minimal additional funding, despite most of its projects being aimed at increasing product. Overall, EU funds cover 84% of the total project costs, indicating that projects that receive EU funding get limited funds from other sources. Significant exceptions are the EuroQCI, Chips JU, EuroHPC, and QuantERA projects, which receive a large part of their support from other sources, particularly from Member States. Albeit the allocated funds for a given year do not reflect the actual expenditure within that specific year, Figure 4 demonstrates a growing allocation of EU funds over the years, with more than half of the total funding concentrated in the last three years (2022–2024).

Figure 3 Percentage of EU funds for various EU initiatives allocated in 2014-2024.



Source: JRC elaboration

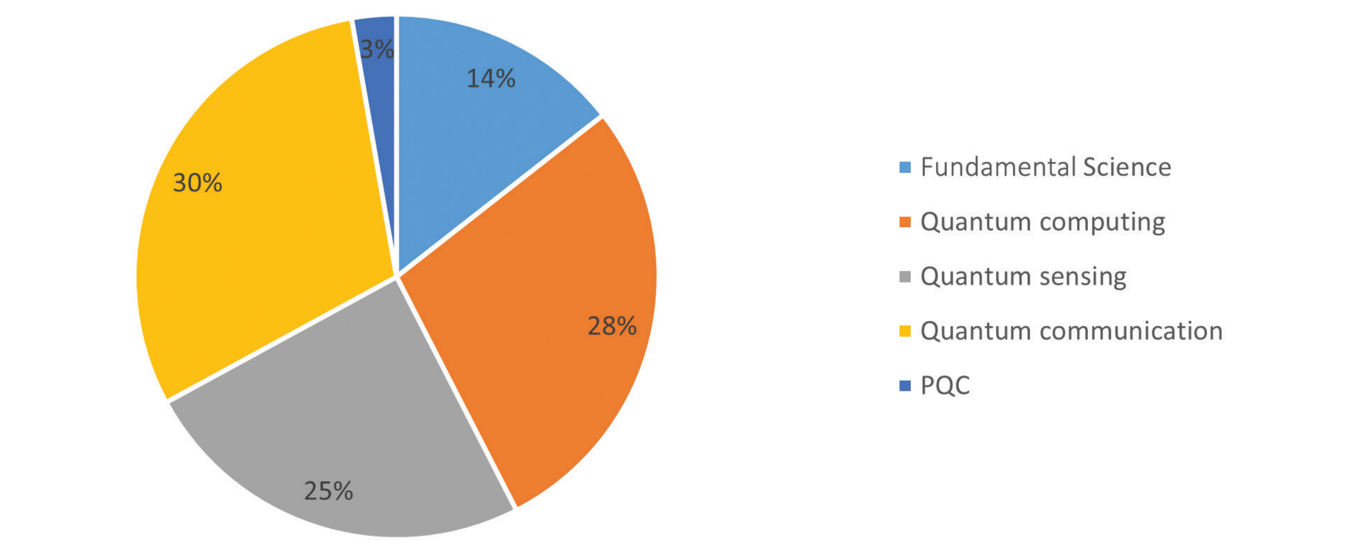
Figure 4 Annual EU funds allocated (million EUR) in 2014-2024 to the EU initiatives



Source: JRC elaboration

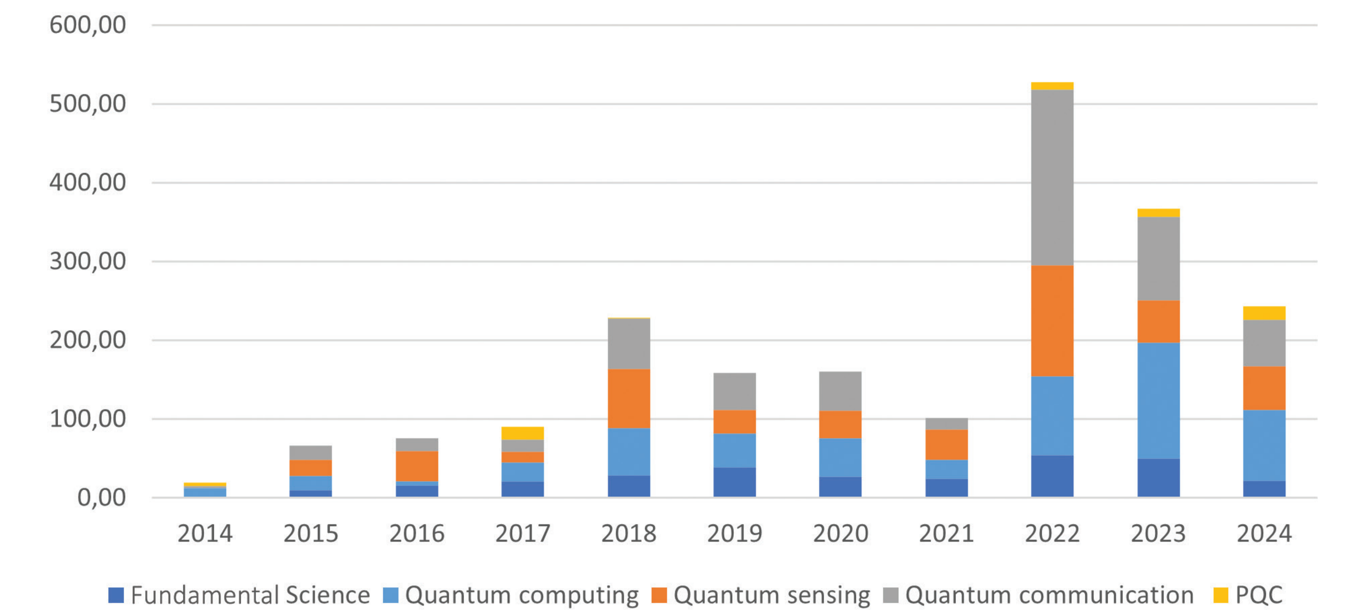
Figure 5 shows the allocation of funds across fundamental science and the various quantum technology areas from 2014 to 2024, while Figure 6 details their annual allocation, using the same methodology as in Figure 4. Funds for projects assigned to multiple technology areas were equally distributed among those areas. Fundamental science received a significant portion of the funds, approximately 14%, highlighting the importance the EU places on quantum research. Among the technology areas, quantum communication received the largest share at 30%, followed closely by quantum computing with 28%, and quantum sensing at 25%. Quantum communication received significant contributions in recent years from the EuroQCI initiatives. PQC received the smallest share, at 3%. This is because PQC is a much more specific area compared to the other domains that encompass a large range of technological solutions and applications. As a result, there is a much smaller number of projects in PQC. The allocation demonstrates that the EU is financing projects across all areas of quantum technologies.

Figure 5 EU funds (million EUR) allocated in 2014-2024 for fundamental science and technology areas



Source: JRC elaboration

Figure 6 Annual EU funds allocated (million EUR) in 2014-2024 for fundamental science and technology areas



Source: JRC elaboration

3.2 The EU's position internationally

In the last few years, the quantum technology sector has experienced a remarkable surge in investments and firm creation. This trend suggests that quantum technologies are gaining increasing economic importance, a phenomenon that has been observable in non-EU jurisdictions for some time, preceding the more recent developments in the EU.

This chapter provides an overview of the global quantum technology landscape, in relation to public and private funding, innovation potential, financial and market perspective and human resource needs.
The analysis addresses quantum technologies following a sector-based classification considering: quantum communications (i.e., essentially QKD), computing, sensing, and PQC. This classification, a novelty compared to the existing reports on quantum, stems from the need to distinguish between quantum key distribution and post-quantum cryptography within the domain of quantum communications. The two fields have experienced different technological developments, idiosyncratic patent evolution and financing trends.

Our analysis focuses on companies developing quantum technology regardless of their size and main business. The sample includes tech giants as Microsoft or Amazon, whose main activity is different from quantum but have strong quantum departments, as well as small start-ups developing specific quantum applications. Official data sources lack information on emerging technologies, making it challenging to identify relevant companies solely by looking at their industrial classification codes. To address this knowledge gap and the complexity of the quantum landscape, this report identified a comprehensive list of firms by looking at both the technologies already developed and those in research and developmental stages.[111] The analysis investigates the geographical coverage of these companies, their investment patterns, focusing on venture capital, and patent applications. Notably, the analysis uses transaction data to contextualise, understand and evaluate the importance of investment activities both within the EU and abroad. Data on patenting activities includes the number of patents filed and granted, as an indicator of potential technology development.

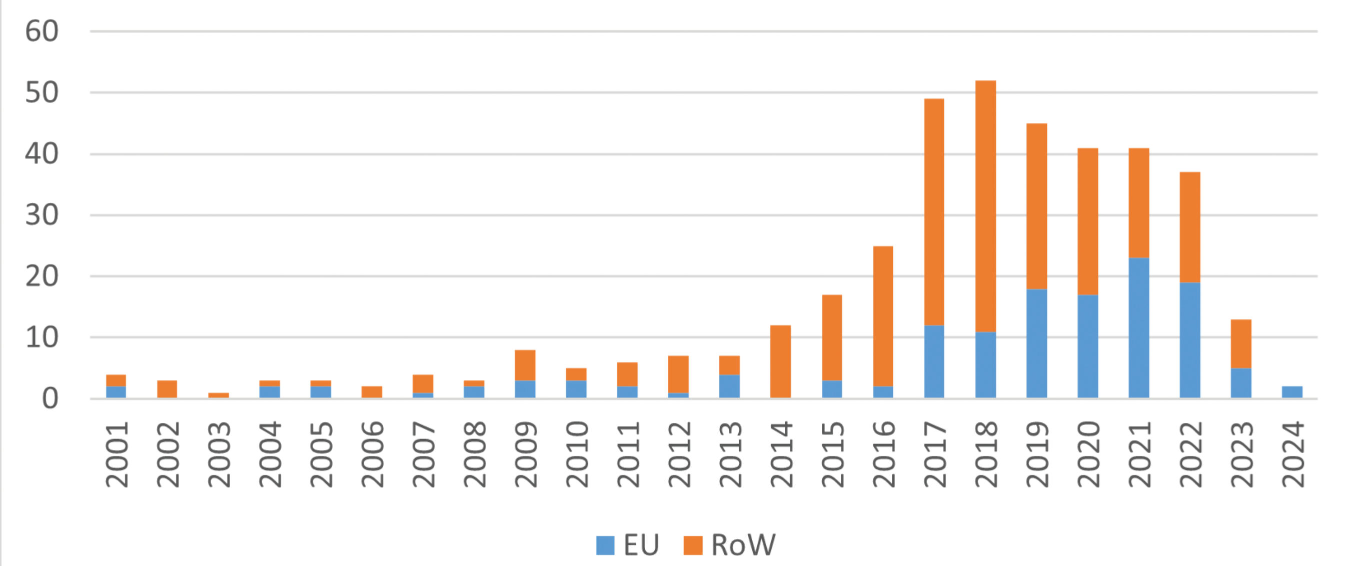
In addition, this chapter also offers a snapshot of the innovation and knowledge dissemination through publications, the public investments and human resources in this sector. The final aim is to assess EU position in terms of industrial capabilities, financing, innovation and skills, and understand the needs for strengthening the presence in the sector.

3.3 Global landscape of quantum companies

A global mapping of the industry has identified over 440 companies, with the majority operating in quantum computing (64%), followed by post quantum cryptography (PQC, 15%), quantum sensing (11%) and quantum communications (10%). About 48% of companies sampled were incorporated between 2001 and 2018, and 41% after 2018 (Figure 7), of which only 8% in the last two years.

111 The identification of these relevant companies was a meticulous process, where each company was carefully reviewed and selected based on expert judgement. Specifically, the authors assessed individual companies one by one, evaluating their involvement in the quantum sector, their areas of focus, and their contributions to the field. Commercial databased, journal articles, conferences and specialised blogs were the main sources used.

Figure 7 Quantum companies by incorporation date and location



Source: JRC elaboration based on Moody's ORBIS data.
Notes: RoW: Rest of the World.

45% of the quantum companies sampled are in Europe (EU, UK and Switzerland), 31% in the EU.
At global level firm creation peaked in 2018. In the EU the peak was reached 3 years later.
13% of EU companies are large or medium. This percentage reaches 29% in the US.

The pace of company creation slowed down after 2018 at global level, with an exception in the EU where the number of companies created per year actually increased until 2021 probably because the EU investment in the sector began slightly later. Notably, this slowdown could be due to the lack of clear commercial implementation, which drove down firm creation in favour of scaling-up. Indeed, venture capitalists, especially US based, showed an increasing preference for scale-up investments, with the share of early-stage Venture Capital (VC) value decreasing since 2017 (see Section 3.5.1).

Out of 441 quantum companies located worldwide, 141 (32%) are based in the EU,[112] about one quarter are located in the US, and 5% of quantum companies are located in China (Table 2). Despite grouping a larger share, EU companies are younger and smaller than those in other jurisdictions such as China and US[113]. Notably, while only 29% of US companies were founded after 2018, in the EU a significant 60% of companies (50% in the case of China) were established during this same period.

Concerning the size, the share of large and medium companies stands at 13% for the EU, while it increases to 29% for the US. The share of large companies is even higher for Chinese quantum firms (82%).

112 In particular, in France, Germany, Netherlands, Spain, Finland and Italy.

113 Size categories follow the Eurostat definition.

Table 2 Companies, share by location

	EU	CH	UK	US	CN
Quantum sensing	35%	2%	13%	29%	6%
Quantum computing	31%	2%	8%	28%	5%
Quantum communications	36%	2%	19%	15%	6%
PQC	28%	4%	16%	28%	4%
Total	32%	2%	11%	27%	5%

Source: JRC elaboration based on Moody's ORBIS data.
Notes: Japan has 13 companies in quantum computing only.

3.4 Innovation and knowledge protection

The number of patents filed in the quantum domain provide valuable information on the innovation potential, since R&D expenditures are usually not available, especially for small companies. Countries with a high concentration of patents in a specific technology area typically possess the necessary set of human skills to become strong players in that field, making patent data a valuable proxy of expected development in the quantum sector.

In the period 2017-24, about 30 thousand patent families[114] related to quantum technologies were filed globally, with 59% for computing, 27% for communications, 10% for sensing and 4% for PQC.

Table 3 Quantum patent families 2017-24: number and compound annual growth rate (CAGR) by filing country

	Number of patent families	CAGR 17-20	CAGR 21-24
CN	14,087	45%	15%
US	7,028	53%	35%
JP	1,882	17%	53%
EU	1,752	50%	52%
KR	972	47%	33%
IN	501	38%	93%
CA	459	29%	26%
UK	454	17%	48%
RU	225	21%	17%
RoW	2,905	70%	8%
Total	30,265	46%	25%

Source: JRC elaboration based on Moody's ORBIS IP data extracted in December 2024

114 A patent family is a collection of applications covering the same or similar technical content. Therefore, all patents belonging to the same family are counted as a single entity. Patent families have been extracted from ORBIS IP using both IPC codes and keyword search in their title, abstract, description or claims. All patents have been revised manually by experts to avoid false positives. Patents families have been classified according to the ultimate owner, enabling a comprehensive assessment of group level patent holdings.

China dominates quantum patenting activities, with Chinese firms owning 46% of the world patents in quantum. The US follows with a 23% share of the world patents, followed by Japan and the EU, grouping 6% of quantum patents each.[115]

In terms of individual technologies, China holds a significant share of patents in PQC (33%), quantum computing (41%) and quantum communications (46%). Specifically on the last one, Chinese companies, such as Quantum CTek, are playing a key role in the development and deployment of such a technology.[116]

The US has a strong lead in quantum sensing, holding 36% of patent families, with many major US companies such as IBM, Microsoft, Google, and Intel leading the race. Finally, also the EU is contributing to the field, ranking fourth in all the four technologies, with a non-negligible share of patents: about 10% in quantum sensing, 9% in PQC and around 6% in both quantum computing and communications. Interestingly, both age and size of companies are reflected in the much smaller share of patents that EU-based firms own.[117]

3.4.1 Recent trends in quantum patenting

As shown in Table 3, **global patenting activity experienced a slowdown, starting from 2021 and primarily driven by the top players, China and the US**. This decline is consistent with the recent decrease in the total number of new companies being established. In the period 2021-24, the Chinese compound annual growth rate (CAGR) in patenting was three times lower than that observed in 2017-20, while US CAGR was one third lower. Interestingly, US slowdown in 2021-24 was mostly due to a lower pace in granted patents, while pending patents were still growing annually at 42% (up from 32% in the period 2017-20). For China instead, both pending and granted patents slowed down considerably in the last four years.[118] **In contrast to the decrease experienced by CN and US, the EU displayed a positive and stable growth in quantum patenting, despite its lower share of global patents. This growth accelerated even further in 2021-24, when the EU CAGR more than doubled compared to the global CAGR**. This recent growth appeared to be driven by an increasing volume of new pending patents.

About 17% of quantum patents globally are owned by research institutions and universities, suggesting that quantum technology is still at the development stage and reflecting the relevance of EU funding programmes in science research. Interestingly, some of the observed patents (35%) are also owned by companies not included in the mapping exercise. These are companies mainly operating in other business sectors (i.e. finance, telecoms, industry) but investing in acquiring knowledge in quantum, since they expect either expanding their business into quantum-related products or leveraging quantum technologies to enhance their core business operations. For example, several central banks have been working on the adoption of quantum technologies, such as quantum computing or post-quantum cryptography, and are trying to include them into banking regulations, with a list of use cases that refer to optimisation and simulation problems as well as fraud detection algorithms.[119] The UK Royal Navy intends for Hercules aircraft to run quantum systems in parallel to their standard navigation systems. Airbus, BAE, QinetiQ, Thales and

115 QUIC (2025) shows a general growing trend in the period 2017-2022, with a total of over 11 thousand patents and a CAGR of 31%, when focusing on computing, sensing, communication (QKD and quantum internet) and excluding PQC. The QUIC analysis also confirms a great dominance of China and USA compared to Europe, slightly above Japan and Korea, with the European patent landscape accounting for about 10% of the total global share. When focusing on international patent families, for example IP5 families, the relative weight of China might decrease. Specifically, IP5 families are patents that are filed in at least two intellectual property offices and with at least one application filed in one of the top 5 patent offices.

116 Mercator Institute for China Studies (MERIC, "China Tech Observatory Quantum Report 2024", available at: https://merics.org/sites/default/files/2024-12/MERICS%20China%20Tech%20Observatory%20Quantum%20Report%202024.pdf

117 Patents (active and pending approval) are sourced from Moody's ORBIS IP. The analysis only considers patent families to palliate the double-counting of similar technologies advancements – especially strong for China. A family is a collection of patent applications covering the same or similar technical content, hence all patents belonging to the same family are counted as a single one. This implies that that the terms patent and patent family are used interchangeably in this report.

118 In the period 2021-24 pending Chinese patents grew at a CAGR of 21%, down from 43% in 2017-20. The slow down for granted patents was even higher, with a CAGR21-24 equal to -12% down from a CAGR17-20 of 53%.

119 On 7 February 2025, Europol hosted a Quantum Safe Financial Forum (QSFF) event, in which the QSFF has issued a call to action for financial institutions and policymakers, urging them to prioritise the transition to quantum-safe cryptography.

Leonardo are all partners with interests in flight-based positioning, navigation and timing systems.[120]

Table 4 Top patent holders not identified as quantum companies, classified by quantum technology

Quantum computing	Quantum sensing	Quantum communications	PQC
PURE STORAGE (US, data storage)	LOCKHEED MARTIN (US, aerospace and defence)	MATRIX TIME DIGITAL TECH (CN, telecom)	WINKK (US, computer system design)
NUFLARE TECHNOLOGY (US, semiconductors)	ROBERT BOSCH (DE, semiconductors)	TENCENT TECHNOLOGY (CN, multimedia)	WELLS FARGO BANK (US, banking)
INDUSTRIAL & COMMERCIAL BANK OF CHINA (CN, banking)	RICOH COMPANY (JP, digital services)	OPPO MOBILE (CN, telecoms)	PAYPAL, INC. (US, financial)
NIPPON TELEGRAPH AND TELEPHONE (JP, telecom)	SEIKO EPSON (JP, printing)	WELLS FARGO BANK (US, banking)	AXON (US, weapons)
BANK OF AMERICA (US, banking)	NORTHROP GRUMMAN (US, defence electronics and systems)	NIPPON TELEGRAPH AND TELEPHONE (JP, telecom)	NIPPON TELEGRAPH AND TELEPHONE (JP, telecom)
TENCENT TECHNOLOGY (CN, multimedia)	QST CORP (CN, semiconductors)	DONGWOO FINE-CHEM (CN, chemicals)	SIEMENS AG (DE, digital technology)
NORTHROP GRUMMAN (US, defence electronics and systems)	ARES TECHNOLOGIES, INC. (US secure data systems and biometric technologies)	DEUTSCHE TELEKOM AG (DE, telecom)	DEUTSCHE TELEKOM (DE, telecom)
SEIKO EPSON (JP, printing)	HONOR DEVICE CO., LTD. (CN, consumer electronics)	SAMSUNG DISPLAY CO LTD (SK, electronics)	ELMOS SEMICONDUCTOR (DE, semiconductors)
ELWHA LLC (US, private equity)	QUALCOMM (US, semiconductors)		VOLVO CAR (SE, controlled by CN, automotive)
PETROCHINA (CN, oil and gas)	TRIPLEPOINT PRIVATE VENTURE CREDIT INC., (US, investment company)		Computer Associates (US, software)

Source: JRC elaboration based on Moody's ORBIS IP data extracted in December 2024.

3.4.2 Openness in patenting collaboration

Quantum firms based in the EU are quite open to collaborative patenting activities in quantum technology across jurisdictions (co-patenting),[121] which involves working with partners from other countries to develop the technologies when filing for a patent. About 23% of the EU patent applications are co-patented with applicants located in non-EU jurisdictions. In contrast, co- patenting only involves 3% of quantum patents for China, 6% for the US and 9% for Japan.[122]

China collaborates mainly with Japan (38% of the Chinese co-patenting is done with applicants in Japan) and with the US (36%), but much less with the EU (2%). Japan reciprocates, with China being Japan's main partner for co-patenting (44%). US instead closely cooperates with Europe, with about 37% of US co-parenting being done with the EU, and a further 28% with the UK. US co-patenting with

Asia is less prevalent, with 11% of patents produced jointly with Japan and only 8% with China. The EU co-patenting also mainly involves US partners (83%).

The share of co-patenting in the EU, despite being higher compared to the US or China, presents large variations depending on the quantum technology considered. In PQC co- patenting activity is very limited (8% of all the patent applications), and it is only done with the US. For quantum sensing, the share is slightly higher (9%) and mostly done with the US or with other European countries (Switzerland and the UK). Co-patenting in QKD affects 21% of patent applications, almost all of them done with the US. The same happens for quantum computing, where 30% of all EU patent applications are made in partnership with entities in another jurisdiction, overwhelmingly in the US.

3.5 Investments

3.5.1 Private investments

At the global level in the last 12 years, **quantum companies received about EUR 6 bn[123] worth of VC financing**. The bulk of quantum VC financing involved quantum computing firms (over three quarters), while quantum sensing and PQC firms obtained about 10% of the funds each.

About 66% of the total money invested was later stage VC, targeting companies that likely were preparing for scaling-up or large-scale expansion. The remaining 34% of funds were destined to financing product development and market entry through early-stage VC. Notably, the large share of scale up VC financing is a feature of quantum sensing (90%) and PQC (77%) technologies, while quantum communications is characterised by a higher share of early-stage VC investments (40%). It is worth noticing that this prevalence of later stage VC investments is a relatively recent trend, emerging after 2020, which indicates a clear change in investment strategies away from early-stage companies and towards more established and mature firms. As a matter of fact, the value of later stage VC in 2020 represented for the first time over half of total value of VC investments in quantum[124] (see Figure 8).

120 See CIPA (2024) and https://www.aerospacetestinginternational.com/features/how-quantum-sensors-will-unlock-aviations-potential.html

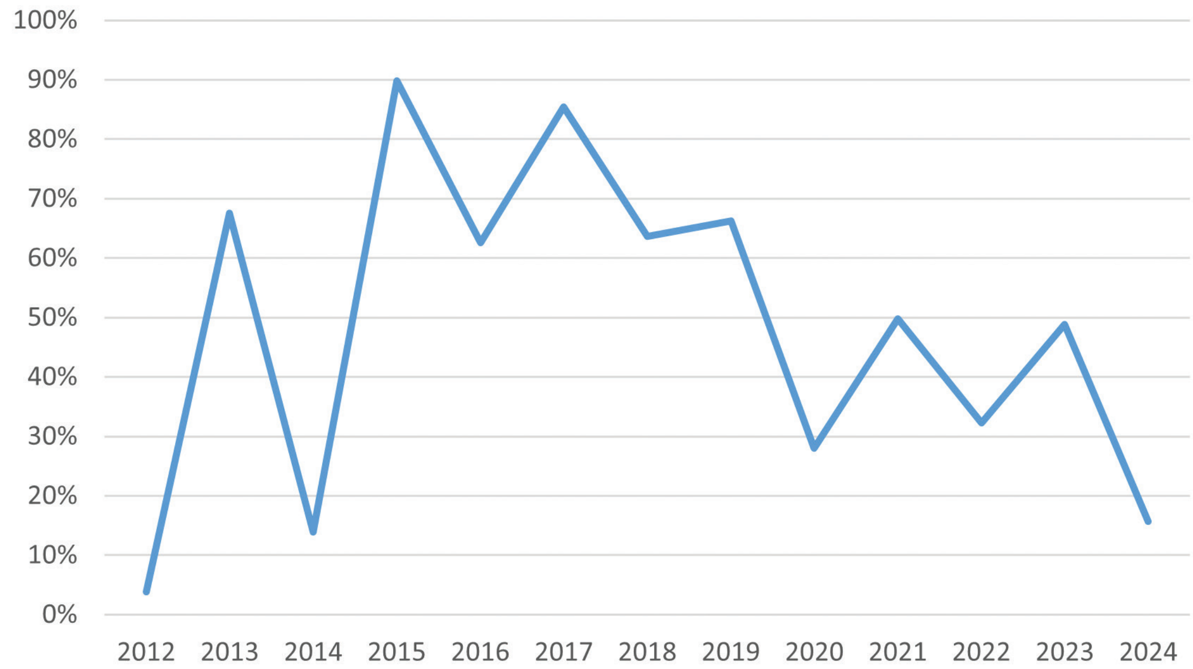
121 Co-patenting means that there is an applicant/inventor from one specific country (or group of countries, as it is for the EU) and at least another applicant/inventor that comes from another country. The non-European applicant could belong to a company of the same group, to a different company or to a foreign university/research institution.

122 In absolute numbers, the EU shared patenting with non-EU entities amount to 695 patent families. For China the patent families jointly developed with a non-Chinese entity are 629, for the US 808, and for Japan 307.

123 This figure (as well as the remaining value aggregates presented din this section) is based on aggregated Pitchbook deal level data. About 36% of VC transactions do not report the value of the investment.

124 The aggregate value of later stage VC investments in quantum firms worldwide between 2020 and 2024 was EUR 3.7 bn, while EUR 1.6 bn were raised by quantum firms in early-stage VC investments globally, based on Pitchbook data (extracted in March 2025).

Figure 8 Early-stage VC funding (share of the value of early-stage VC transactions over total value)



Source: JRC elaboration based on Pitchbook data extracted in March 2025.
Notes: About 36% of VC transactions do not report the value of the investment.

Potential quantum technology market size by 2040: USD 70 bn- USD 173 bn.[125]

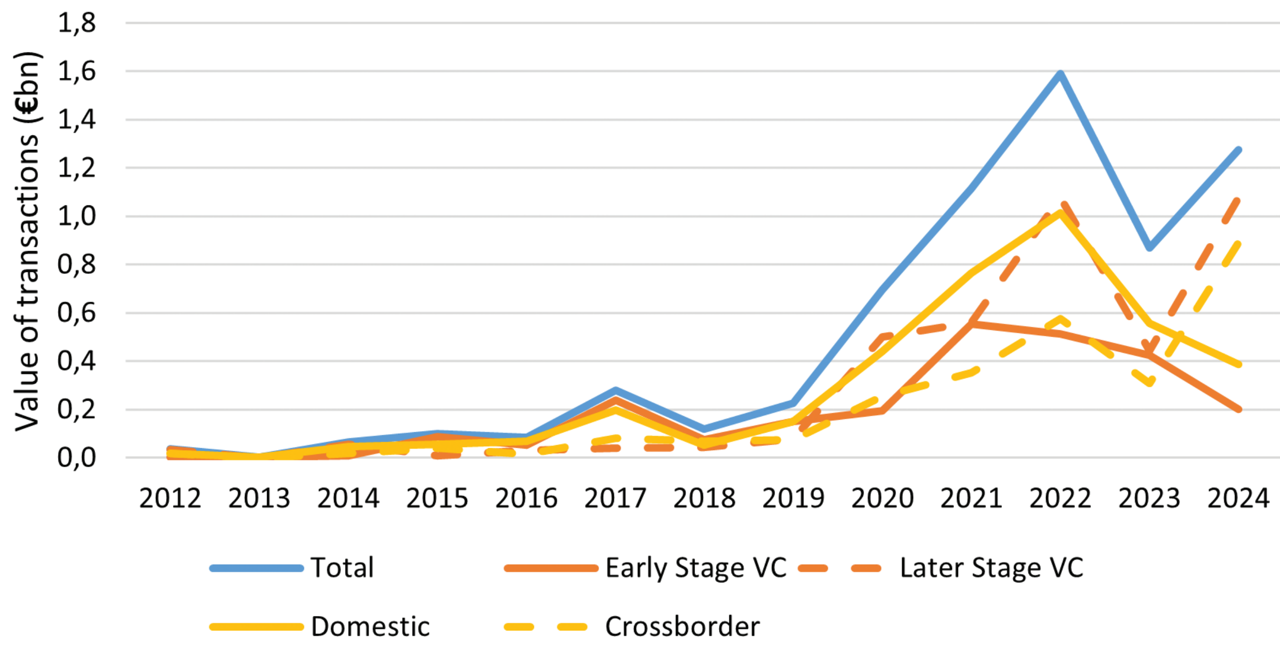
Four industries are likely to see the earliest economic impacts from quantum computing: chemicals, life sciences, finance and mobility. Potential gain up to USD 2 trillion in 2035.[125]

Interestingly, most VC investments were directed to domestic companies,[126] with EUR 2.5 billion (or 42% of capital invested) involving cross-border financing (Figure 9 and Figure 10). This trend was particularly accentuated for quantum sensing technologies, where the domestic VC investments reached up to 80% of the total. Investments in PQC and quantum communications were also largely domestic in nature (74% and 75% of the total for each technology, respectively), and the only technology with more international movement of private investments was quantum computing (44% share of cross-border investments). However, more recently, data reveals a shift towards increased cross-border investments, thus suggesting a maturing industry with companies that are becoming better positioned to compete in the global market.

125 McKinsey, "Quantum Technology Monitor," available at: https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantum-technology-monitor-april-2024.pdf

126 That is, target quantum companies located in the same jurisdiction as the VC investor.

Figure 9 Annual aggregate value of VC transactions (in EUR bn), total and by types of VC investment



Source: JRC elaboration, based on Pitchbook data extracted in March 2025. "Domestic investments" are those where the VC investor HQ is located in the same jurisdiction as the target quantum company, while "cross-border investments" are those where the two parties are located in different jurisdictions. Notes: About 36% of VC transactions do not report the value of the investment.

Between 2012 and 2024, **EU-based[127] venture capitalists led the investment landscape participating in 27% of all investments, closely followed by US-based investors, who were present in 26% of investments**. However, **the value of US-participated VC investments** in all quantum technologies in this period was EUR 2.3 bn, **more than doubling the value of EU participated VCs** (EUR 1 bn)[128]. Looking at the ranking of these top two investor jurisdictions across individual quantum technologies, the **EU also was the main jurisdiction of VC investors in quantum computing**, but not in the remaining three technologies. In PQC and communications the US ranked first, followed by the EU in both cases, while in sensing the UK ranked first, followed by the US and by the EU in third place.

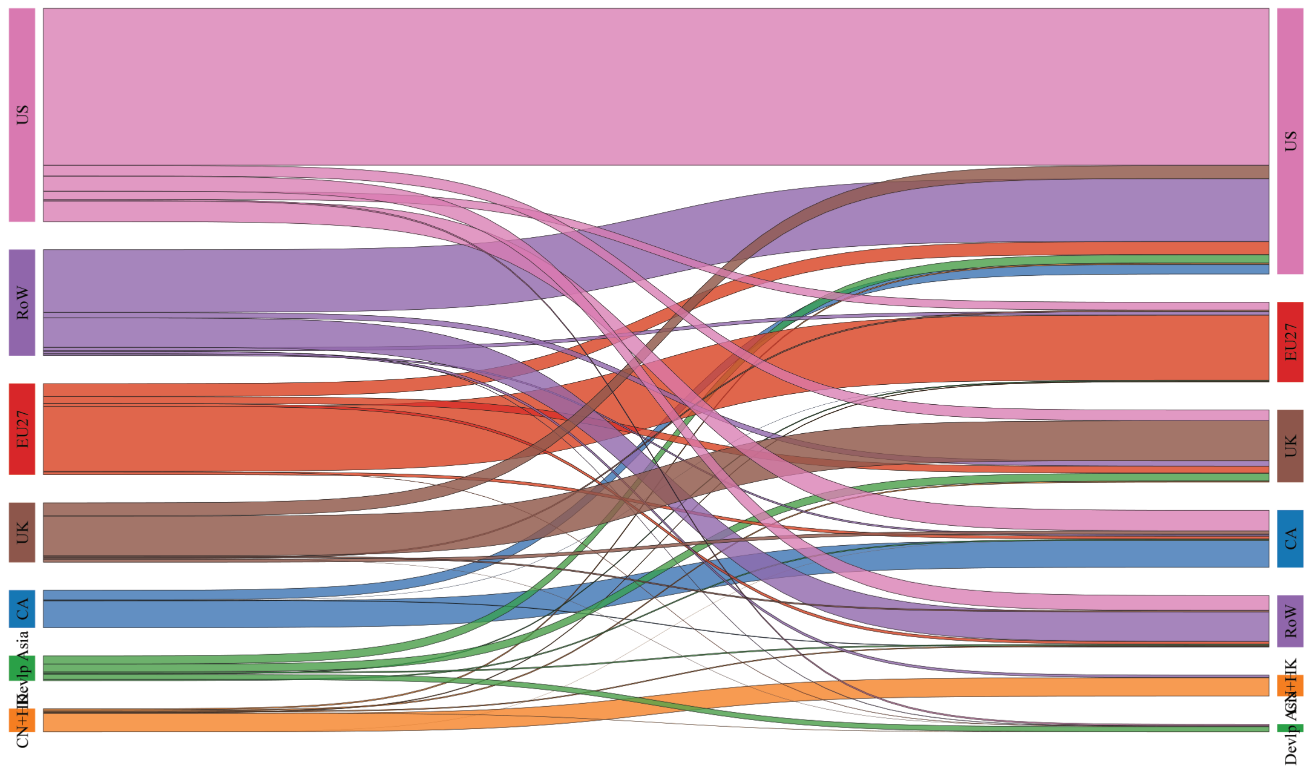
In terms of the geographic distribution of these VC investments in 2012-24, US quantum firms received the largest amount of funds (EUR 2.9 bn), followed by **EU firms which attracted significantly less, with EUR 862 m**, approximately one third of the US total.[129] UK-based quantum firms placed third, collecting EUR 788 m in VC investments. Focusing on EU companies, they primarily attracted investments from the US and UK (Figure 10). Interesting, when EU venture capitalists look to invest in non-EU based quantum companies, they tend to focus on US- and UK-based quantum companies, thus suggesting a reciprocal flow of investment between the countries (Figure 10).

127 In particular, EU VC investors were based in France, Germany and the Netherlands.

128 For comparison, Chinese VCs invested EUR 252 m.

129 For comparison, Chinese quantum firms received EUR 229 m in VC investments.

Figure 10 Intra-country/region and cross-country/region flows of VC investment values (2012-2024)



Source: JRC elaboration, based on Pitchbook data extracted in March 2025. Notes: Location of investors (left) and quantum target companies (right) is determined based on HQ location. About 36% of VC transactions do not report the value of the investment. The "Developed Asia" category includes Japan, Taiwan, South Korea, and Singapore. China includes Hong Kong. RoW: Rest of the World. CA: Canada.

Points for debate

- What does VC need so that it can address the requirements of quantum?
- How can we bring VC and quantum together?

3.5.2 Public investments

The public sector plays a significant role in driving global investment in quantum technology, the total amount reaching approximately 49 billion EUR to date.[130] Several countries have in fact defined national strategies and allocated specific funds for research and development activities in the sector. **While the US accounts for about 13.5% of the total, the EU accounts for more than 20%**. For China, for whom quantum technology is a key priority area in industrial policy, announced figures range from USD 3 billion to USD 15 billion in investments.[131 132] Such an interest is driven by an ambitious plan to create a general quantum computer and simulator by 2030. Caution should be exercised in interpreting such figures, estimates differ between sources, are highly dependent on the different time-periods to which official statements refer, and on whether they report allocated or spent funds.

130 https://www.qureca.com/quantum-initiatives-worldwide/.

131 ITIF, "How Innovative Is China in Quantum?", https://itif.org/publications/2024/09/09/how-innovative-is-china-in-quantum/

132 China is launching a 1tn yuan ($138 bn) government-backed fund to support emerging technologies, including quantum computing, in a bid to strengthen its global competitiveness. Source: Reuters: reported https://thequantuminsider.com/2025/03/07/china-launches-138-billion-government-backed-venture-fund-includes-quantum-startups/

Nevertheless, it may be stated that **the largest contribution to EU public funding for quantum technology comes from Member States, primarily France and Germany, EC programmes contributed more than EUR 2 billion and ESA projects an additional EUR 0.5 billion**[133]**.**

3.6 A skilled workforce for the quantum sector

A skilled workforce is essential to promote the research base and translate it into industrial leadership across the various quantum sectors, e.g. quantum computing, communication, sensing, and simulation. The ability to research, develop, deploy, and utilise quantum technologies relies heavily on a human capital with deep scientific understanding of the matter and practical technical expertise. As shown in Section 3.8 on the publications, a mix of competences is required, not only experts in quantum physics, but also experts in related areas, such as mathematics, materials science, computer science, and engineering.

Data on the size of the quantum workforce remains scarce and unreliable, as standard employment databases do not adequately capture the nascent sector yet. The current workforce is mainly formed by highly academic experts (i.e. PhD level) representing the only trained people in quantum [45]. The current quantum job market in the world is dominated by quantum computing- related positions, despite potential near-term opportunities in other areas like sensing and communication [46].

When progressing from the current early development to a more mature market, the quantum sector is expected to increase the demand of personnel with different levels of training and competences [47]. Projections estimate a substantial growth in quantum jobs, with company Qureca based in UK forecasting 600,000 new positions by 2040, increasing concerns about having enough skilled workers to fill them.

The lack of skilled workers is of concern already today. In 2022, a study reported that on average there is a qualified quantum candidate for every three job openings[134]. In 2023, approximately 68% of leaders from quantum firms indicated that the acquisition of personnel is a key challenge [48].

While the requirement of PhD degree in the job openings remains high, we are also witnessing a shift toward lower degrees. In 2020, a PhD degree in a quantum-related field was required in 67% of the job openings in EU, about 15% higher than the requirement in US and Canada [47]. This gap can be explained also by the different quantum areas (e.g. communication vs. computing) and industrial involvement (e.g. large companies vs. SME and research centres) of the two regions. More recently (2023-24), the quantitative analysis of job postings worldwide shows that the requirement for a PhD degree decreased significantly (reaching 31% in EU and 35% in US), while the requirements for Bachelor and Master graduates combined make up a larger portion of the total job positions available (40%) [46]. This trend toward lower educational qualifications can be the result of the increased maturity of the sector (e.g. passing from the lab to products) as well as a way to attract applicants even if they may not have the desired higher degree.

In the global talent shortage, Europe is considered well-positioned in terms of quantum talents and quantum-relevant graduates. As a matter of fact, one of the key strengths of the European quantum industry is the ability to develop talent. The United Kingdom has the highest per capita densities of quantum talent (over 1 800 per million people), followed by the United States (around 1 000) and then the EU (around 700).[135] Remarkably, Denmark

133 The Quantum Europe Strategy puts Member State public funding at more than EUR 9 bn over five years. At country level, Germany and France have committed EUR 3 bn and EUR 1.8 bn respectively according to QURECA, or EUR 4.9 bn and EUR 2.0 bn respectively according to McKinsey, in their 2024 Quantum Technology Monitor. Other EU countries such as Austria, Denmark, Finland, Hungary, the Netherlands, Spain, and Sweden have national quantum initiatives worth EUR 1.75 bn overall. The UK has committed GBP 3.9 bn (EUR 4.6 bn), while Switzerland plans to invest CHF 10 (EUR 10.6 m), source McKinsey.

134 McKinsey, "Quantum computing funding remains strong, but talent gap raises concern," available at: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-funding-remains-strong-but-talent-gap-raises-concern

135 See European Investment Bank, "A quantum leap in finance – How to boost Europe's quantum technology industry," European Investment Bank, 2024, available at: https://www.eib.org/en/publications/20220112-a-quantum-leap-in-finance-executive-summary

has the world's highest concentration of graduates enrolled in quantum-relevant education.[136]

At the policy level, the **EU is actively implementing strategies to address the quantum skills gap and foster the development of a quantum-ready workforce**. Launched in 2018, the Quantum Flagship (see Section 2.1) explicitly includes training and skills development as a key objective alongside its goals in research, innovation, and industrialisation. In particular, the Quantum Technology Education Coordination and Support Action (QTEdu CSA)[137] plays a vital role in bridging the gap between the academic and industrial quantum communities. Its initiatives, such as the QTEdu Open Master (QTOM)[138] pilot project, explore innovative educational models like online course exchange and local accreditation to enhance accessibility to specialist quantum expertise for students in broader STEM programmes. Moreover, the Digital Europe Programme (DEP) further demonstrates the EU's commitment by funding specific workforce development initiatives like Digitally Enhanced Quantum Technology Master (DigiQ)[139] and Quantum Technology Courses for Industry (QTIndu).[140] The European institute of Innovation and Technology (EIT) runs occasional schools and courses in quantum technology subjects itself and also promotes the DEP initiatives.[141] These programmes aim to scale up the training of quantum professionals and upskill the existing workforce.

An initial outcome of the EU initiative promoting quantum education is already visible. **The number of master's degree programmes related to quantum technologies rose to 55, a 10% year-over-year increase[134]**. These programmes are designed to equip graduates with the specialised knowledge and skills needed to enter the quantum workforce. Furthermore, there is a growing emphasis on providing hands-on experience to students through internships in both university research laboratories and industrial settings. This practical engagement is crucial for developing job- ready skills valued by the quantum industry.

Given the rapid evolution and diverse landscape of quantum technologies, a **curriculum focusing on core quantum principles and generic quantum technologies** (instead of focusing on specific ones) is the most suitable for forming a class of skilled workers adequately prepared also for any future challenge. A quantum-ready workforce requires more than just quantum physics knowledge. It necessitates a multidisciplinary skill set which includes non-quantum specific skills such as programming and relevant lab experience (e.g., cryogenic) as well as soft skills. The most effective curricula would need to prioritise the fundamental theoretical quantum background with practical experience, for instance through industrial traineeships, adopt an interdisciplinary approach, and offer diversified training programmes from Bachelor, to Master, to PhD. Re-skill programmes for active workers are also important for meeting immediate industry demands by leveraging the transferable skills.

Besides quantum curricula, it is important to **integrate quantum concepts into current education ("quantum enhancing")** in fields like computer science and engineering to create a broader talent pool. For this scope, it would be also essential to increase quantum literacy at lower education levels by educating teachers and introducing quantum ideas early on.

The knowledge dissemination and transfer of dual-use technology such as those related to quantum, may require additional precautions. A point open for debate is how to raise the dual-use awareness, introduce precautions in disseminating information and acknowledging conflicting values (i.e., harms and benefits of a technology) so that an ethical dual-use dissemination can be conducted [49].

136 KPMG, "Quantum technology in Denmark," Nov. 2020, available at: https://assets.kpmg.com/content/dam/kpmg/dk/pdf/dk-2020/11/Quantum-technology-in-Denmark.pdf

137 QTEdu website at: https://qtedu.eu/

138 QTEdu Open Master Pilot webpage at: https://qtedu.eu/project/qtedu-open-master-pilot

139 DigiQ website at: https://digiq.hybridintelligence.eu/

140 QTIndu website at: https://qtindu.eu/

141 EIT quantum skills digital academy website at: https://www.eitdeeptechtalent.eu/calls-and-opportunities/quantum-skills-digital-academy/

Points for debate:

- In the ongoing 'global race for talent' and future increasing needs of the quantum sector, how can we best attract and retain new students and talents without impacting other sectors?
- Are upskilling and reskilling initiatives enough? What innovative strategies can be implemented?
- Given the rapidly evolving and diverse landscape of quantum technologies, how should education balance specialisation in specific quantum areas with interdisciplinary skills to meet both current and future industry needs?
- How to raise the dual-use awareness, introduce precautions in disseminating information and acknowledging conflicting values in research and knowledge dissemination of dual- use quantum technology?

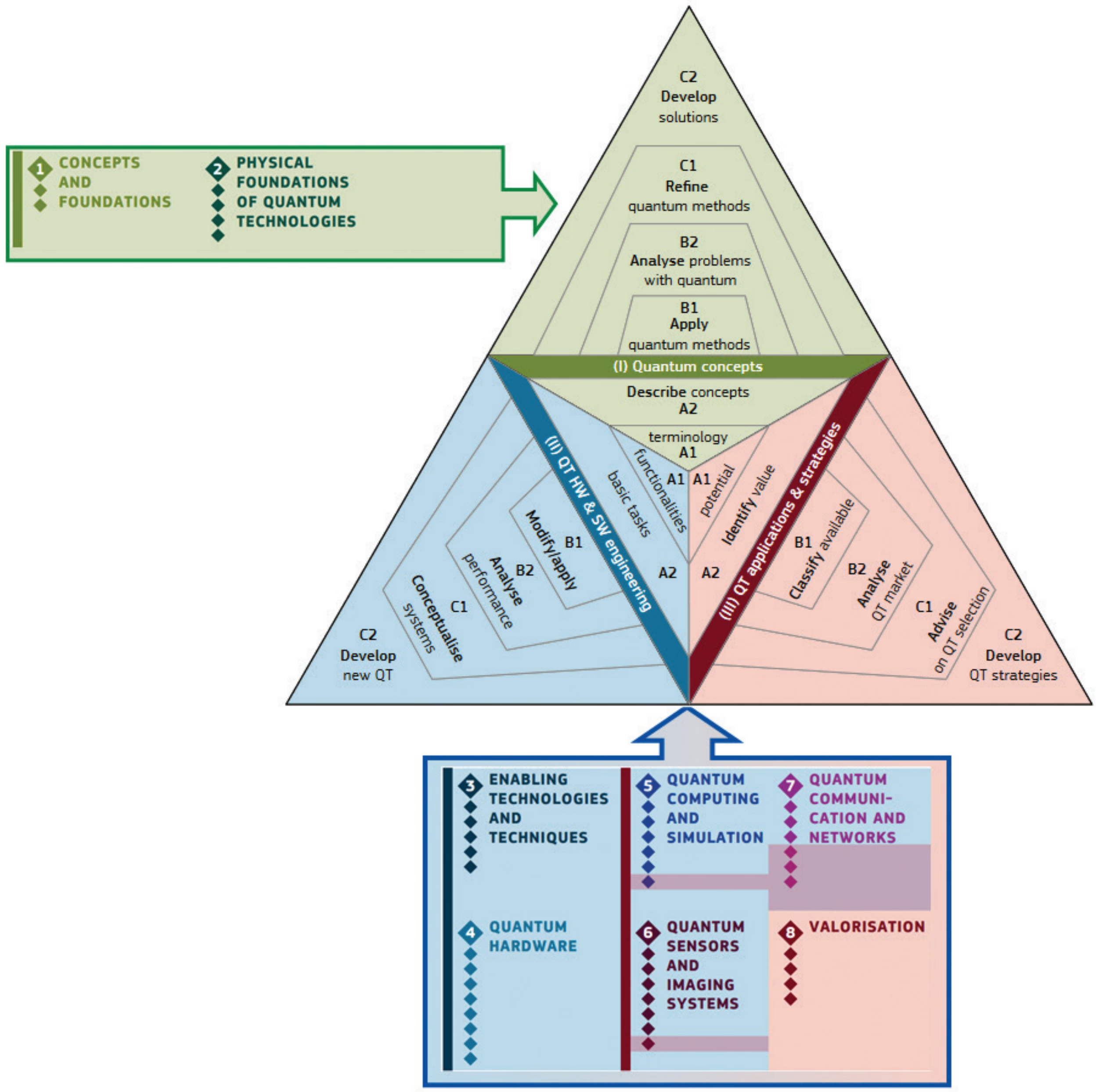
Released in April 2025 by the QTEdu Coordination and Support Action (CSA) of the Quantum Flagship, the **European Competence Framework for Quantum Technologies (CFQT)** is a taxonomy of the specific knowledge, skills, and qualifications required across the quantum technology landscape, facilitating the design of targeted education and training, the hiring process and the self-assessment. Based on input from the community and analysis of interviews, the Competence Framework has been updated twice by the Quantum Flagship CSA QUCATS.

The framework identifies various qualification profiles, such as the quantum-technologies "aware person," "literate person," "business analyst," "engineering professional," and "core innovator", providing examples of competence sets for different roles. These profiles are structured around six proficiency levels, ranging from A1 (Awareness) to C2 (Innovation). Based on the European Qualification Framework (EQF), the levels correspond to Bachelor's (B2), Master's (C1), or PhD (C2) degrees, or equivalent work experience. These levels are mapped into three proficiency areas: Quantum concepts, hardware & software engineering, and applications & strategies (Figure 11).

The CFQT is accompanied by a certification scheme that offers measurable proficiency level descriptions and sample examinations, including example tasks and assessment scenarios for different levels. The certification scheme is expected to help enhance practical applications and broader impact of the CFQT.

The CFQT framework will be regularly updated to reflect the rapidly evolving nature of quantum technologies. The European Quantum Readiness Center (EQRC) will also play a role in promoting the adoption of the framework for both educational institutions and for employee hiring and upskilling, potentially leading to the formal recognition of quantum qualifications in the future.

Figure 11 The European Competence Framework for Quantum Technologies



Source: adapted from QTEDU website

3.7 Key findings from secondary sources

Here we draw attention to some salient findings from other major reports.

A critical analysis of several sources [142],[143],[144] shows that public investments in quantum technology by major players (USA, EU and Member States, China, Japan, UK, Canada) are broadly in line with their economic capabilities: each of these countries have announced total public investment amounting to USD 1-5 billion up to now, for the coming 5 to 10 years. Some caution is required in dealing with these figures, since what exactly is counted as quantum technology varies, the field is rapidly developing, and financial data change continuously. Advertised public spending may, or may not, include industrial contributions or refer to promised money, rather than committed. The excitement around the sector has sometimes led to misunderstandings and mistakes. In particular, the figure of public investment on quantum technologies by China is overestimated by most market reports, with several factors contributing to obfuscate the true scale of Chinese quantum investments: economic indicators from China's central government are sometimes not reliable, regions tend to announce investments to outcompete each other, and Western stakeholders tend to amplify the strategic and business threat coming from China to attract policymakers attention and public investments. To give an example, the funding for the Hefei National Laboratory for Quantum Information Sciences announced in 2017 was reported in the western press to be USD 10 billion[145] while the true figure is an order of magnitude smaller[146]. A carefully sourced report from Rand Corporation[147] details China's public quantum investments as on par with similar investments in the USA and Europe, in the broad range of USD 2 bn to USD 4 bn across 10 years.

According to the McKinsey report,[142] when it comes to private investments in quantum technologies, the USA and Canada (and to a lesser extent the UK and Israel) are the only countries in which private fundings broadly match public ones (USA: USD 3.75 billion public, USD 3.8 billion private; UK: USD 4.3 billion public, USD 1.5 billion private, cumulative). In China, EU countries, Japan, Korea, private investments are less than a tenth of public funding. This in part reflects a more risk-taking approach, and in part depends on the fact that in USA are based the largest corporations active in the quantum computing area (Intel, Google, IBM, etc). However, by looking at the EU figures (Germany: USD 5.2 billion public, USD 104 million private; France: USD 2.2 billion public, USD 113 million private, Netherlands: USD 1 billion public, USD 40 million private [142]) it is clear that EU R&D cost in quantum technology falls disproportionately on public shoulders and private companies have yet to commit fully. A December 2024 article by "The Economist"[148] pointed out the difference between the USA and the Chinese funding models of quantum technologies, where the latter relies essentially on public money, a view reinforced by the fact that in February 2024 two large private Chinese companies (Alibaba and Baidu) announced they have pulled out of the quantum computing race,[149] leaving only Tencent (and Huawei to a much lesser extent) as a Chinese major private player.

It should be pointed out that **expectations of economic returns from investments in quantum computing are huge, especially when compared with its technology maturity**: McKinsey predicts that by 2035 its potential

142 McKinsey, "Quantum technology monitor", April 2024, https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantum-technology-monitor-april-2024.pdf

143 Yole Intelligence "Quantum Technologies: 2023 Market and Technology Trends", 2023, https://www.yolegroup.com/

144 Qureca, https://www.qureca.com/

145 See e.g. https://www.bloomberg.com/news/articles/2018-04-08/forget-the-trade-war-china-wants-to-win-the-computing-arms-race

146 See the testimony before the House Permanent Select Committee on Intelligence on the July 19, 2018 "China's Threat to American Government and Private Sector Research and Innovation Leadership" by Elsa B. Kania of the Technology and National Security Center for a New American Security, https://www.cnas.org/publications/congressional-testimony/testimony-before-the-house-permanent-select-committee-on-intelligence, page 4 and footnote

147 Rand Corporation "An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology", February 2022, https://www.rand.org/pubs/research_reports/RRA869-1.html

148 "China is catching up with America in quantum technology", Economist, Dec. 2024, https://www.economist.com/business/2024/12/31/china-is-catching-up-with-america-in-quantum-technology

149 "Alibaba and Baidu Cash Out on Quantum Computing Stakes," IEEE Spectrum, Febr. 2024, https://spectrum.ieee.org/china-quantum-computer-alibaba-baidu

economic value (defined as the additional revenue and saved costs that the application of QC can unlock) will be in the range of USD 0.9–2 trillion in the four industries (chemicals, life sciences, finance, and mobility) which according to their analysis are the most likely to realise this value earlier than other industries.[142] Actually, as of 2025 the additional value and saved cost of quantum computing is null, since any practical utility of available quantum computers (quantum annealers and noisy-intermediate scale quantum processors) is still to be demonstrated, as previously discussed in Section 1.1. It is presently impossible to give a reliable estimate for the economic value of quantum technologies and in particular for quantum computing in ten years' time, as shown e.g. by the careful analysis presented in the reports by Ezratty.[150] Even some market reports are starting to sound more cautious. For example, Yole acknowledges that with respect to their previous analysis "We overestimated quantum markets, and it will take longer than expected. [...] End- applications and use-cases are still unclear. [...] Quantum computing will probably take another 10 - 20 years of R&D. [...] Only cryptography and sensing/timing have a market value today, and both are still small-market".[151]

Despite these large cumulative investment figures, according to McKinsey[142] **both in 2022 and in 2023 there was a decrease of private investments in quantum technology**: in 2023 private investment in quantum technology startups amounted to USD 1.7 bn, decreasing by almost 30% with respect to 2022. Other sources[152] put the VC quantum investment in 2023 at USD 1.2 billion, with a 50% year on year decrease, which reaches 80% reduction if only North America is considered. It is doubtful that venture capital can support a 10+ years technology challenge without being distracted on the route by more appealing opportunities: according to McKinsey, in the last two years Artificial Intelligence has attracted private capital previously directed to quantum. In these conditions, large corporations (e.g. IBM, Intel, Google) which can sustain the required expensive long-term research effort without tapping venture capital will be advantaged. The lack of large EU companies in the quantum computing effort constitutes a vulnerability, since EU players will be more reliant on fleeting private capital and on public spending. EU public support for quantum should be put on a basis sustainable for the long term and must be commensurate with reasonable expectations. Venture investments in quantum technology reached a high of over USD 2 billion in 2022, indicating strong investor confidence in this emergent market. However, by 2023, this investment decreased by approximately 50%[152], prompting discussions of a "quantum winter".[153] Dramatic swings from over- optimism to excessive pessimism are characteristic of venture capital trends in technology, as shown for example by the variation in stock values of quoted quantum computing firms after a declaration of NDVIA's CEO that 20 to 30 years are still needed for useful applications of quantum computing, and the ensuing rebuttals it elicited.[154] A need for tempered expectations is called for, with a focus on long-term research and development and a clear understanding that the practical applications of quantum computing could be still years away. Although quantum technology remains a niche sector which accounts for less than 1% of total VC funding, the marked decrease in private funding for quantum which has recently taken place in North America is a cautionary tale that once venture capitalists become more aware of the risks and uncertainties associated with quantum technologies, they may rethink their commitment therefore depriving the field of significant resources; this may affect also EU-based companies, which according to our investigations (see Section 3.5.1) attracted nearly EUR 900 million in 2012-2024.

The 2024 European Investment Bank Report "A quantum leap in finance: how to boost Europe's quantum technology industry"[155] shows that "early-stage financing in Europe is significant in comparison to other regions, but later-stage growth financing is substantially lacking" and that "European companies are behind when it comes to raising rounds of more than EUR 2 million" and attributes this to a knowledge gap between investors and the quantum industry

150 O. Ezratty, "Mitigating the quantum hype", 2022, https://arxiv.org/abs/2202.01925; "Understanding Quantum Technologies", 2024, https://www.oezratty.net/wordpress/2024/understanding-quantum-technologies-2024/

151 Yole 2023, pg. 4 "What we got right, what we got wrong".

152 IQM "State of quantum 2024: understanding the 2023 trends and outlook for 2004", January 2024

153 E.g., see "Why you shouldn't be worried about talk of a 'quantum winter'" by J. McKenzie, Physics World, March 2024, https://physicsworld.com/a/why-you-shouldnt-be-worried-about-talk-of-a-quantum-winter/

154 CNBC, "Nvidia's Jensen Huang is 'dead wrong' about quantum computers, D-Wave CEO says," available at: https://www.cnbc.com/2025/01/08/nvidia-ceo-jensen-huang-is-dead-wrong-about-quantum-d-wave-ceo.html

155 European Investment Bank "A quantum leap in finance: How to boost Europe's quantum technology industry", 2024, https://www.eib.org/en/publications/20220112-a-quantum-leap-in-finance-executive-summary

which prevents scaling up financing to reach the USD 100 million scales required for commercialisation. An alternative explanation is that each EU country tends to support its national champions for each of the technology platforms currently investigated, thus fragmenting the funding effort into too many players. In the last 10 years, the number of quantum startups in the EU has markedly increased, but they grow more slowly than their counterparts in the USA, fail to attract sizable investment and remain at the earlier stage of development process, thus hindering the translation of EU scientific excellence into successful commercial ventures.

3.8 Scientific and technical publications

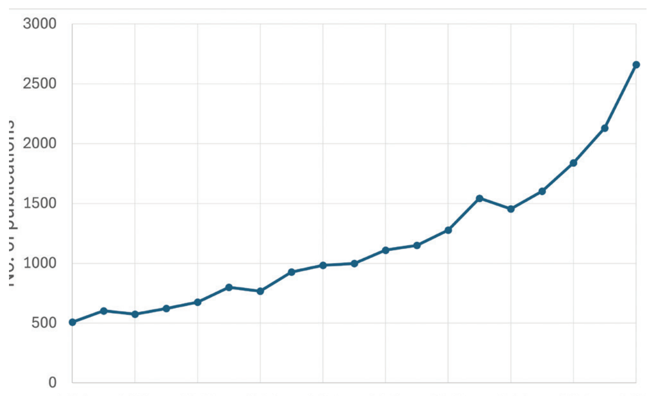
This section assesses the R&D in the quantum sector through a quantitative analysis of the scientific and technical publications. The quantum sector is subdivided into the areas of quantum communication, quantum computing and quantum sensing, subdivided into cold atom interferometry, nitrogen vacancies, and Rydberg atoms.

Our methodological approach is based on query searches on the Scopus database.[156] The keywords for the query are tailored to filter the results in quantum communication, computing and sensing, subdivided as above.[157] Compared to similar analyses available in other studies, in the following the EU publications are aggregated, rather than shown by Member State. It must be borne in mind that this method has an intrinsic degree of subjectivity, because it depends on the selection of the keywords and the use of such keywords by the authors in the publications. Although the query may miss some publications or include others more focused on loosely related areas, overall, it is a powerful tool able to capture the overall trends in the quantum sector.

In the figures below we have separated EC funded work into Seventh Framework, Horizon 2020 and ERC, where stated by the papers' authors, or else counted it simply as European Commission funded. The "total EU" funding refers to publications from projects financed by EC programmes and/or Member States.

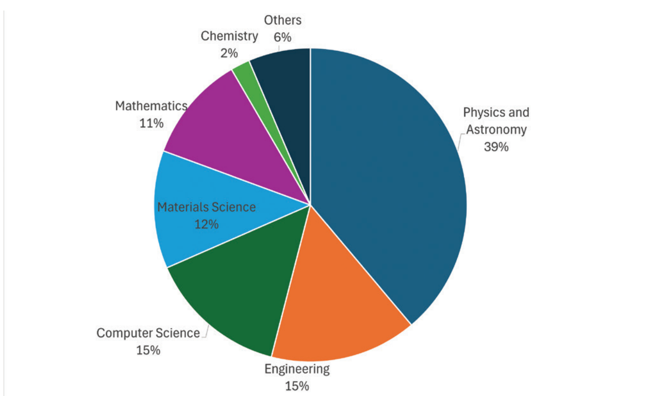
3.8.1 Publications on quantum key distribution (QKD)

Figure 12 Number of publications on QKD in the period 2006-2024



Source: data from Scopus downloaded on 1/7/2025

Figure 13 Subject areas of the publications on QKD in the period 2000-2024

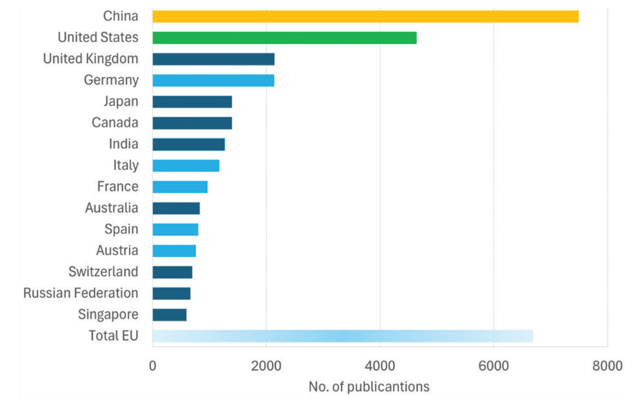


Source: data from Scopus downloaded on 1/7/2025

156 Scopus website at: http://www.scopus.com

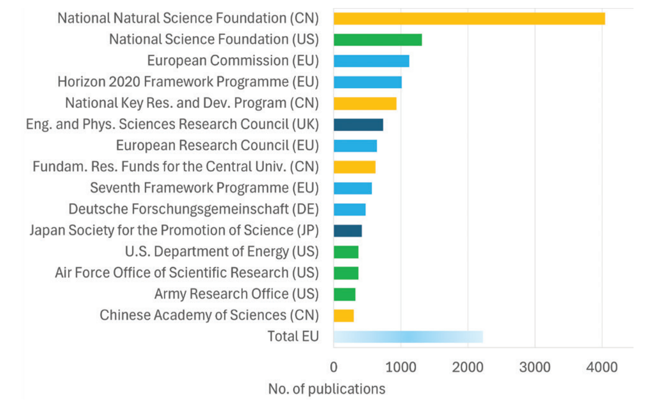
157 Although some false positive or negative results can present in the filtered output, the aggregated results capture the trends of each sub-sector and the role of the main contributing countries.

Figure 14 Top countries of the affiliations of the authors on QKD in 2000-24



Source: data from Scopus downloaded on 1/7/2025

Figure 15 Main funding agencies of the publications on QKD in the period 2000-24



Source: data from Scopus downloaded on 1/7/2025

In the field of quantum key distribution,[158] the yearly number of publications is tripled in about 12 years, from 2013 to 2024 (Figure 12). The publications are mainly focused in the area of physics, followed by engineering, computer science, mathematics and material science (Figure 13). This indicates that fundamental physics plays a key role in developing new solutions, given the rather low readiness level of the technology. However, the engineering of the solutions and inter- disciplinarity are also important in this sector.

When looking at the authors of these publications, Figure 14 **the main affiliation country is China closely followed by EU**. The US is placed only third, with 30% less publications than EU (bar at the bottom of the figure). Figure 15 lists the sources of funding leading to the highest number of publications. In the EU, EC funding (e.g., Horizon 2020 framework programme, European Research Council) is very effective in promoting publications, whereas the publications funded by EU national programmes reach about 80% of the EU funded ones. It is also interesting to notice that India has a number of publications similar to Canada and Japan.

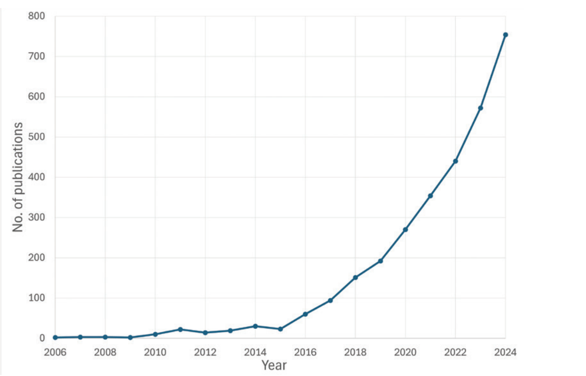
3.8.2 Publications on post-quantum cryptography

For post-quantum cryptography, the publications per year, the subject areas, the country of authors' affiliation, and the funding sponsors are shown in Figure 16 to Figure 19. The number of publications is limited compared to the other quantum areas (i.e., 3015 results overall). It is interesting to note the steep increase from 2016, when NIST launched their public competition (Figure 16). The main subject areas is computer science, followed by mathematics, and engineering (Figure 17).

When looking at authors' affiliations, the EU is leading, followed by China and US (Figure 18). For the funding of publications (Figure 19), the EU is positioned second after China.

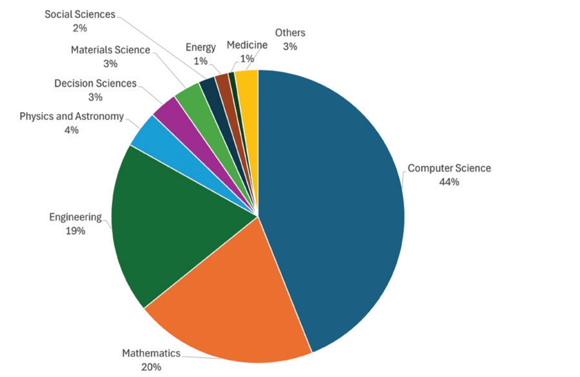
158 The query has been carried out on "quantum communication" and "QKD", with their related sub-fields and technologies (e.g., security proof, quantum protocols, entanglement, single photon detection, quantum receivers, quantum repeaters, trusted nodes, quantum random number generators, quantum key management system).

Figure 16 Number of publications in PQC in the period 2006-2024



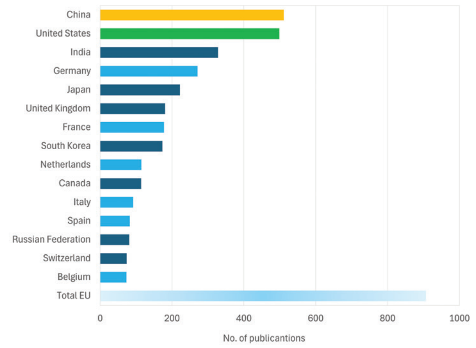
Source: data from Scopus downloaded on 1/7/2025

Figure 17 Subject areas of the publications in PQC in the period 2000-2024



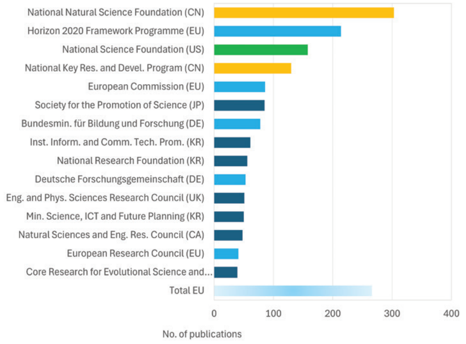
Source: data from Scopus downloaded on 1/7/2025

Figure 18 Top countries of the authors' affiliations in PQC in the period 2000-2024



Source: data from Scopus downloaded on 1/7/2025

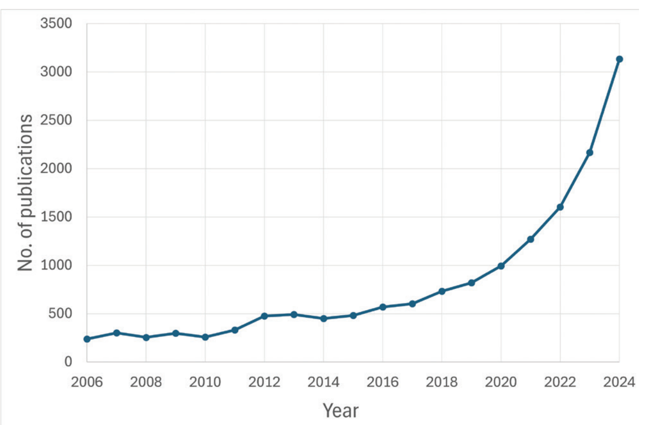
Figure 19 Main funding agencies of the publications in PQC in the period 2000-2024



Source: data from Scopus downloaded on 1/7/2025

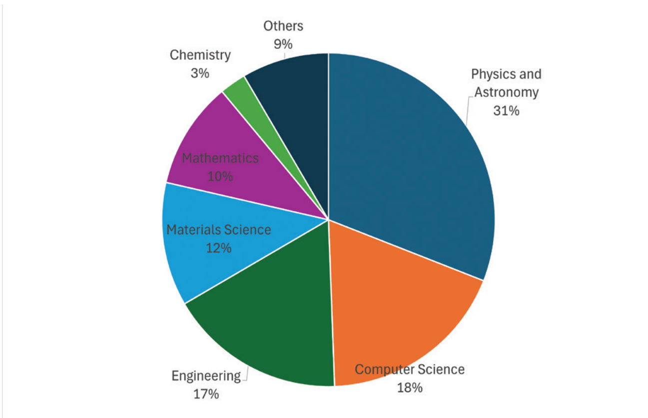
3.8.3 Publications on quantum computing

Figure 20 Number of publications in quantum computing in the period 2006-2024



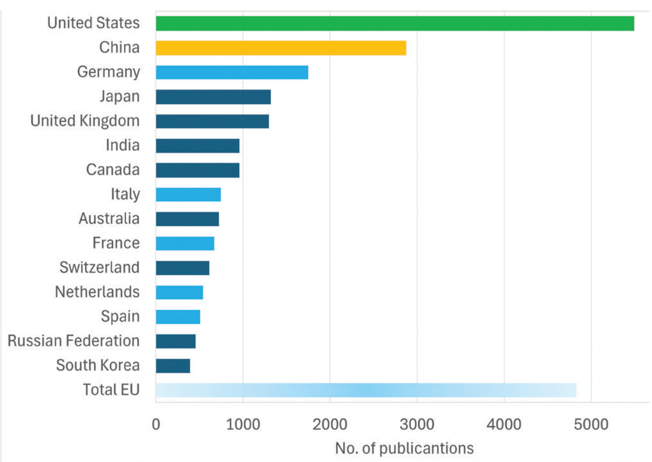
Source: data from Scopus downloaded on 1/7/2025

Figure 21 Subject areas of the publications in quantum computing in the period 2000-2024



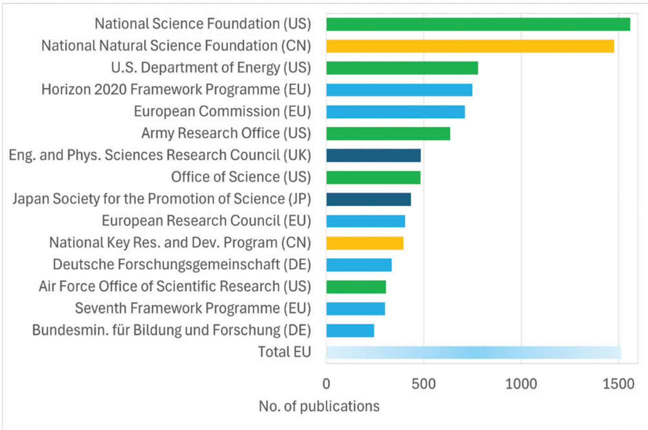
Source: data from Scopus downloaded on 1/7/2025

Figure 22 Top 10 countries of the affiliations of the authors in quantum computing in the period 2000-2024



Source: data from Scopus downloaded on 1/7/2025

Figure 23 Main funding agencies of the publications in quantum computing in the period 2000-2024



Source: data from Scopus downloaded on 1/7/2025

For the publications in quantum computing,[159] we included also the areas related to quantum simulation, quantum emulation and quantum sampling. The number of publications per year has increased by more than 6 times in the last 10 years (Figure 20). **From 2017, the increase has a compound annual growth rate (CAGR) of 27%**.

As seen for quantum communications, about one third of the publications are focused in the area of physics, followed by computer science, engineering, material science and mathematics (Figure 21). The need for solutions at the level of fundamental physics is at the heart of research, followed by engineering the solutions in an inter-disciplinary way.

US is leading in the number of publications, closely followed by EU, while China places third (Figure 22). The main EU affiliations are the Centre National de la Recherche Scientifique (CNRS) in France, Delft University of Technology in Netherlands, Technische Universität München in Germany, Consiglio Nazionale delle Ricerche in Italy, Universität Innsbruck in Austria and the others follow. The knowledge and competence in the sector appear to be widespread

159 The query has been carried out on quantum computing, emulation, simulation and sampling fields, with their related sub-fields and technologies (e.g., quantum neural network, quantum annealing, quantum algorithm, fault tolerance, error correction, quantum coherence, cryogenic systems, superconducting, trapped ions, photonic integrated, neutral atoms, silicon spins, quantum dot, colour-centre in diamond).

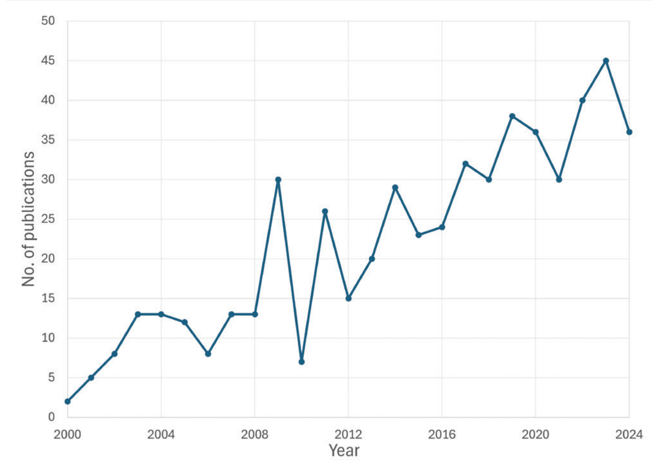
in all the different EU states, although with a different degree and expertise.
The sources of funding are shown in Figure 23. In the EU, EC funding (e.g., Horizon 2020 framework programme, European Research Council) is slightly most effective in promoting publications than the EU national programmes.

3.8.4 Publications on quantum sensing

The field of quantum sensing is extremely diversified, and an investigation on scientific publications using generic queries such as “quantum sensing” gives only an average picture showing tens of thousands of papers in 2000-2024, with a steady increase in the publication rate, but does not show the trends going on in the different areas. In addition, the absence of more targeted keywords in the query adds a significant number of false positives in the results, thus increasing the risk of wrong interpretations. We present in the following sub-sections three different specific cases (namely, sensors based on cold atom interferometry, on nitrogen vacancies in diamond, and on warm vapours of Rydberg atoms), to highlight how the standing of EU research strongly depends on the specific technology under examination and the targeted applications.

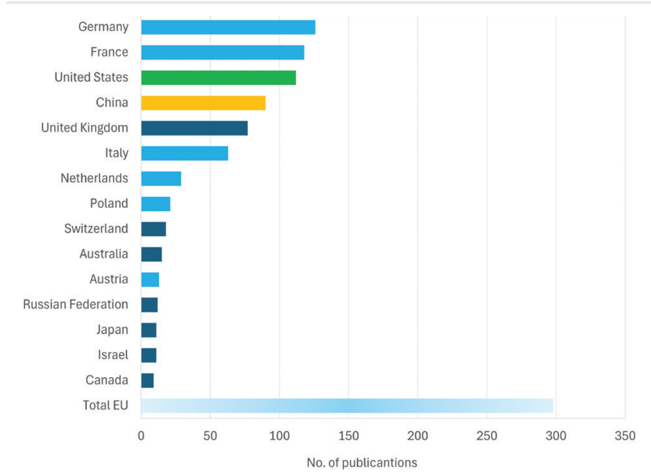
3.8.4.1 Publications on cold atom interferometry

Figure 24 Number of publications on cold atom interferometry in the period 2000-2024



Source: data from Scopus downloaded on 17/4/2025

Figure 25 Top countries of the affiliations of the authors in cold atom interferometry in the period 2000-2024

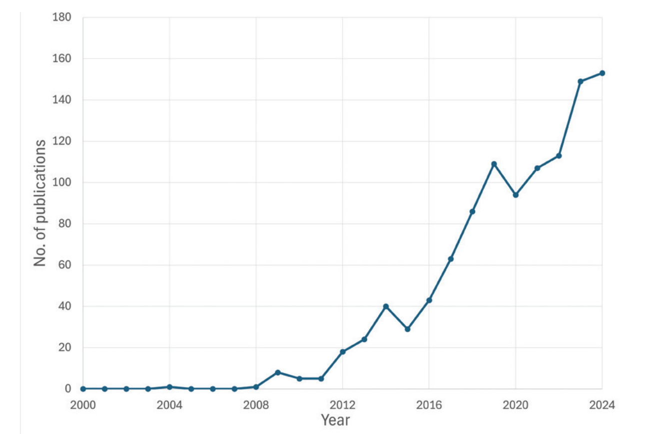


Source: data from Scopus downloaded on 17/4/2025

The publication rate in the field of cold atom interferometry has been steady for more than two decades (Figure 24), with countries such as France, Germany, Italy, and Netherlands bringing the EU at the leading edge among the main international players (Figure 25). Additional analysis of the data shows that the EC with its various programmes is the first among the funding entities, while the enhanced potential of CAI)-based sensors in microgravity explains the presence of national and supra- national space agencies (DLR, ESA, CNES); metrology institutes, in particular from France and Germany, are also present. With some caution, cold atom interferometry can be taken as an EU success story, where fundamental physics research is being (slowly) translated into applications for Earth and planetary sciences and is also being deployed in space.

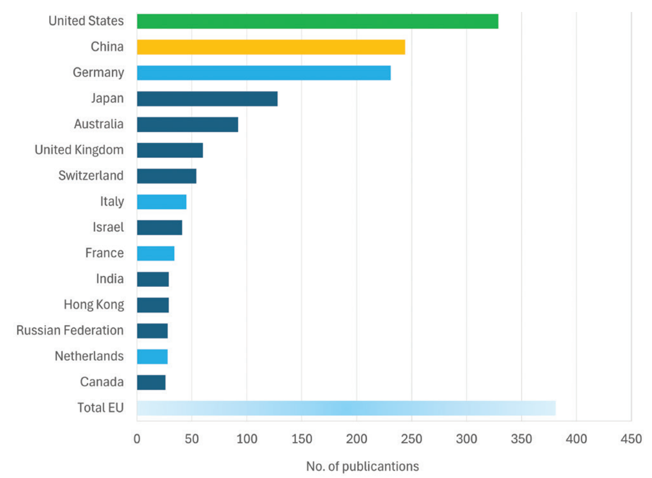
3.8.4.2 Publications on nitrogen vacancies in diamonds

Figure 26 Number of publications in nitrogen vacancies in diamond in the period 2000-2024



Source: data from Scopus downloaded on 17/4/2025

Figure 27 Top publishing countries in nitrogen vacancies in diamond in the period 2000-2024



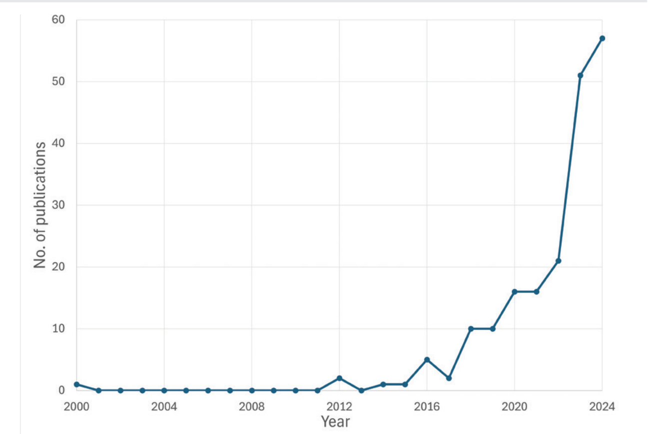
Source: data from Scopus downloaded on 17/4/2025

Nitrogen vacancies in diamond[160] as a sensing platform have been investigated for at least 15 years (Figure 26), and the EU is well positioned in the publication landscape (Figure 27): Germany is by far the main contributor, followed by Italy, France, and the Netherlands. The EC, with its Horizon 2020 and ERC programmes, is among the principal funding entities, and institutes of excellence in EU are the Ulm and Stuttgart universities, which compete with much larger players such as the University of Science and Technology of China, MIT, and Harvard.

The flexibility of this solid-state sensing platform operating at room temperature is at the basis of the variety of the use cases that can be addressed, which includes areas such as biology and medicine, where the biocompatibility of diamond represents an important advantage. Small and low-cost sensors are potentially possible but there are unresolved issues concerning the growth of suitably doped and pure materials. Indeed, our analysis shows that a significant fraction of the publications deal with material science.

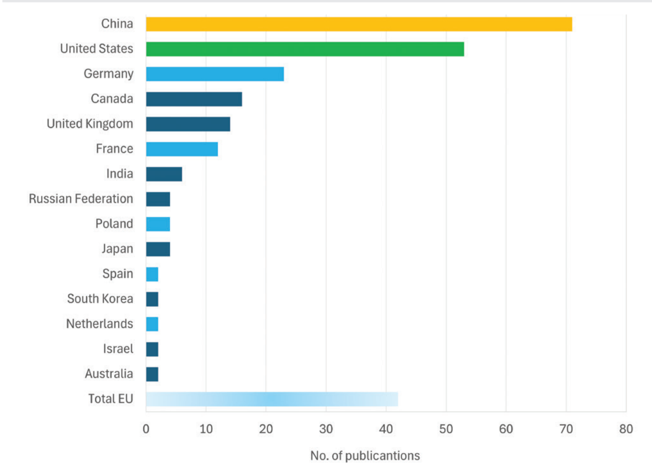
3.8.4.3 Publications on Rydberg atoms

Figure 28 Number of publications in sensors based on Rydberg atoms, in the period 2000-2024



Source: data from Scopus downloaded on 17/4/2025

Figure 29 Top publishing countries in sensors based on Rydberg atoms in the period 2000-2024



Source: data from Scopus downloaded on 17/4/2025

160 The query has been carried out on nitrogen vacancy diamond for sensing.

Warm vapours of Rydberg atoms as a sensing platform started to attract the attention of researchers only 10 years ago (Figure 28). A clear and abrupt increase in publication rate started in 2015, and NIST played a pioneering role with their 2014 paper [44]. In this area, NIST had a clear advantage because of the enabling technologies it developed for the chip-scale atomic clock (CSAC) in 2000- 2010. Defence represents a driving factor for applications, notably for RF communications: the US Defense Advanced Research Projects Agency (DARPA) is funding several programmes targeting compact ultra-wideband RF antennas for military communications. A quick catch-up by China explains the steep rise in the publication rate in the last three years, which leaves the USA in second position and the EU (with Germany, France and Poland) in third, see Figure 29.

The interest of this platform for defence applications is confirmed by an in-depth investigation on the funding entities, which shows, as first players, the National Natural Science Foundation of China, the Ministry of Science and Technology of the People's Republic of China, the National Key Research and Development Program of China, DARPA, U.S. Department of Defense, but also the Chinese National University of Defense Technology, the US Air Force Office of Scientific Research, the U.S. Army Research Laboratory, and Defence Research and Development Canada. EU programmes come a distant third, after those of China and the USA. Among the authors' affiliations we find some start- ups (Quantum Valleys Ideas Laboratories from Canada and Rydberg Technologies, a dedicated spin- off from the University of Michigan at Ann Arbor), but also metrology institutes such as NIST and the National Institute of Metrology China, which can easily be explained by the possible use of Rydberg atom as RF measurement standards. We can conclude that in this area the potential military applications have driven a research effort that has left the EU trailing behind its main competitors.

4 Standardisation and regulation

4.1 *Standardisation for quantum technology*

The benefits of standardisation for quantum are typical of high technology in general: to reduce costs and improve efficiency, ensure the quality and safety of products and/or services, comply with relevant legislation, satisfy customers' expectations and requirements, enable access to global markets, achieve compatibility/interoperability between products and/or components and disseminate knowledge about new technologies and innovations [43].

In the EU, standardisation takes place within a defined legal framework. Specific standards can be requested from the EU Standards Development Organisations (SDOs) by the European Commission and standards can be used in EU harmonised legislation.[161] Although the latter has not happened yet for quantum technology, quantum technology and post quantum cryptography are priority subjects in the EU standardisation work programme.[162] Accordingly, CEN-CENELEC is active through its Joint Technical Committee on quantum technology (JTC22), ETSI through its technical Committee on Cybersecurity (TC CYBER) and its Industry Specification Group on quantum key distribution (ISG QKD). CEN-CENELEC JTC22 currently has working groups on quantum metrology, sensing and enhanced imaging, and quantum enabling technologies; quantum computing and simulation and on quantum communication and cryptography. It also publishes a Standardisation Roadmap for Quantum Technology.[163] The Quantum Europe Strategy recognises the importance of standardisation for industrialising quantum technology and therefore plans to publish an EU roadmap in 2026. We understand that this will lay out plans for support for standardisation, complementing, not competing with, the CEN-CENELEC document.

Worldwide, several other organisations are developing standards or making recommendations, including ISO/IEC, ITU-T, IEEE, IETF and GSMA and, from the Quantum Flagship, QUIC and QUCATS, to the point where there is something of an embarrassment of riches, too many competing standards being as bad as not having standards at all. Moreover, it has become difficult for industry to follow everything and know which standards to work towards. The CEN-CENELEC Roadmap is valuable in providing an overview and the establishment of an IEC/ISO Joint Technical Committee specifically for quantum technologies (IEC/ISO JTC3) should, it is hoped, bring order to this situation.

Quantum technology does play one special role in standardisation: as a tool in metrology, including to realise base units, for example caesium fountain atomic clocks, Josephson junction voltage standards and quantum Hall effect resistance standards.[164] New metrology techniques are also being developed to assess quantum devices, so quantum technology and metrology serve each other. In Europe, including beyond the 27 EU Member States, this area is the responsibility of EURAMET (see Section 2.7) and the relevant working group of JTC22.

Having the greatest impact currently, although not strictly speaking quantum technology themselves, are standards for the transition to PQC/quantum-resistant cryptographic algorithms.[165] Finalised standards for PQC algorithms published last year by the US NIST, following several years of proposals and evaluation, are for lattice-based key encapsulation, lattice-based digital signature and hash- based digital signature. ETSI TC Cyber's working group on quantum-safe cryptography[166] has preferred to issue recommendations supporting the NIST initiative, rather than develop a European alternative. Examples are for quantum-safe digital signatures, public key encryption and key encapsulation and efficient hybrid key exchange with hidden access policies. Other PQC standards and recommendations have been issued by ISO/IEC, IEEE, GSMA and IETF and by the German Federal Office for Information Security (BSI).

161 Parliament/Council Regulation (EU) No 1025/2012 on European standardisation

162 Commission Notice (C/2025/1818) of 27th March 2025 on the 2025 annual Union work programme for European standardisation

163 CEN-CENELEC JTCC 22, Standardization Roadmap on Quantum Technologies, Release 1.1 June 2025 https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Quantum%20technologies/Documentation%20and%20Materials/fgqt_q06_standardizationroadmapquantumtechnologies_release1-1.pdf

164 In metrology, the word "standard" may refer to the apparatus rather than the document.

165 EUROPOL, "Quantum Safe Financial Forum - A call to action," available at: https://www.europol.europa.eu/publications-events/publications/quantum-safe-financial-forum-call-to-action

166 ETSI webpage on Quantum-Safe Cryptography (QSC) at: https://www.etsi.org/technologies/quantum-safe-cryptography ETSI, "Quantum-Safe Cryptography (QSC)" https://www.etsi.org/technologies/quantum-safe-cryptography

Communication was the first area of quantum technology to be the subject of a serious drive for standards **and remains, unquestionably, the area for which standardisation is best developed**, especially for quantum key distribution, as evidenced by ETSI specifications and reports[167], ITU-T recommendations on networks supporting QKD[168] and the first ISO test standard in the area.[169] Of the ETSI specifications, those for application programming interfaces (API) stand out for having been taken up by several vendors, showing that standards for interoperability are among the most valuable. JTC22's working group on communications has planned its work items to avoid any duplication with ETSI; some experts participate in both committees.

Quantum communication has now advanced to the point where industry would like to have its products independently certified to assure customers of their cybersecurity effectiveness. One vendor, ID Quantique of Geneva, already offers a quantum random number generator (QRNG) certified by several national authorities. QRNG certification is relatively straightforward because the fact that it is a quantum device does not change the certification criteria, which depend on the statistics of the output. ID Quantique do also advertise their Clavis XG complete QKD system as having been authorised for use with classified information by the Republic of Korea National Intelligence Service, which is a unique achievement. In the EU, the appropriate framework for future cybersecurity certification of quantum devices is the EUCC scheme, see next section. A key step towards this was the publication in 2024 of ETSI GS QKD 016 "Common Criteria Protection Profile-Pair of Prepare and Measure QKD modules", which defines the high-level requirements that a device under test must meet.

In quantum computing, standardised metrics by which machines can be objectively compared, ideally independently of the technology platform, would be of immense value. Some experts also argue that it is already time to start standardisation of quantum computing architecture. The need for standards for quantum computing software is becoming very clear, although it may be that de facto software standards will emerge naturally from competition between companies and the best path for the SDOs will be to formalise them. All these subjects are being addressed by JTC22.

Apart from complete devices, there is a strong case that certain **components and enabling technologies** are ready for standardisation. JTC22 has taken radiofrequency (RF) and dc connectors, travelling-wave parametric amplifiers, ion traps and entangled photon-pair sources as cases. It has not yet created work items for quantum sensing and imaging, but the Roadmap mentions magnetometers and photonic devices as possible subjects.

Europe is in a very strong position in quantum standardisation. Care must be taken to **maintain this advantage to protect the interests of EU industry**, but without provoking negative reactions and making it an arena of conflict.

For all technology sectors, global standards are seen as optimal: "one standard, one test – accepted everywhere", so international agreements exist to pass activity up to international SDOs unless there are specific reasons why national or regional standards are necessary. The Vienna and Frankfurt Agreements between CEN-CENELEC and ISO/IEC define conditions when work should be halted on EU standards in a sector and the items passed up for development of global standards. At present, the new joint technical committee on quantum technology IEC/ISO JTC3 has not yet defined its strategic business plan; disagreements, mainly between non-European members, have slowed progress, so it is pragmatically accepted that CEN-CENELEC JTC22 should continue to work independently. Nevertheless, IEC/ISO JTC3 is maturing and has established ad hoc working groups on sensors, secure communication, computing and simulation, quantum random number generators and quantum enabling technologies. One work item has been passed to it: that on terminology, which is now the subject of three projects in IEC/ISO JTC3. Agreement on the meaning of terms should help all further discussions.

167 ETSI, "Industry Specification Group (ISG) on Quantum Key Distribution for Users (QKD) Activity Report 2023," available at: https://www.etsi.org/committee-activity/activity-report-qkd

168 ITU-T documents Y.3800 to Y.3828

169 ISO/IEC 23837 Security requirements for QKD, Part 1 and Part 2

Points for debate:

- What quantum standards will be important and should be prominent in the roadmap?
- What areas are premature for standardisation?
- What is the best balance between developing European standards and promoting them globally, versus representing European interests in global standards development organisations?

4.2 Legislation, cybersecurity, EUCC certification framework

Quantum communication technology is now at the point where security certification is needed. The regulatory framework addressing certification of ICT products has been rapidly evolving in the past years towards the creation of a digital single market and the enabling of trade within the EU. The EU Cybersecurity Act (Regulation (EU) 2019/881) and Commission Implementing Regulation (EU) 2024/482 establish a harmonised approach to cybersecurity across the EU, under the responsibility of the European Union Agency for Cybersecurity (ENISA). The Act establishes a framework for certifying the security of ICT products, services, and processes, including the European common criteria-based Cybersecurity Certification scheme (EUCC), a voluntary scheme based on the widely recognised ISO / IEC 15408 series standards, known as the Common Criteria. EUCC is the successor to the SOG-IS framework already used across 17 EU Member States. It is the appropriate framework for certification of quantum communication systems.

Common criteria evaluation is carried out by a relatively small group of laboratories, denominated Information Technology Security Evaluation Facilities (ITSEFs), officially accredited to conduct evaluations according to ISO / IEC 15408 and Common Evaluation Methodology ISO / IEC 18045. Certificates are issued by a separate group of organisations called Certification Bodies, using the results of tests carried out by ITSEFs.

The standards define a set of stringent criteria against which a product can be evaluated in terms of functional security, security architectures, product development environment, handling identified vulnerabilities in the product, according to Evaluation Assurance Level, EAL1 to EAL7, with higher numbers corresponding to greater rigour. To achieve a particular EAL, a system must meet specific assurance requirements, involving design documentation, analysis, functional or penetration testing. Systems that provide multilevel security, such as those required for QKD, are evaluated at a minimum of EAL4, typically EAL4+, the level foreseen in the ETSI protection profile. This entails an evaluation of whether the device has been methodically designed, tested, and reviewed, plus an advanced methodical vulnerability analysis and verification of the development and support processes.

4.3 Trade control

Quantum technologies are perceived as pathbreaking. Although still in their infancy, they can bring a strategic advantage to the country that is able to deploy them first. Moreover, some quantum devices are "dual-use"; they can be used for civilian or military purposes. Various countries are putting trade control and supply-chain decoupling measures in place, on the grounds of national security.

In EU, the Regulation 2021/821[170] based on the Wassenaar Arrangement includes some quantum- related items[171] as dual-use. In addition, in 2024, some EU countries have added quantum technologies to their national control list of dual-use items.

170 Regulation (EU) 2021/821 of the European Parliament and of the Council of 20 May 2021 setting up a Union regime for the control of exports, brokering, technical assistance, transit and transfer of dual-use items, https://eur-lex.europa.eu/eli/reg/2021/821/oj/eng

171 EU Regulation 2021/821 includes: "Systems, equipment and components designed to use or perform QKD, also referred to quantum cryptography (5A002.c)", and "The technology for the development or production of equipment of quantum wells (3E003.b) and superconductive electronic devices (3E003.c)".

In the US, in September 2024, the Bureau of Industry and Security (BIS) established a new rule[172] regarding export controls for advanced technologies, including quantum technologies. The affected items relevant for the quantum sector are: (i) CMOS (Complementary Metal Oxide Semiconductor) integrated circuits and parametric-signal amplifiers that can operate at very low temperature, (ii) materials containing certain silicon (Si) or germanium (Ge) isotopes, which have no nuclear spin and thus can be used to develop spin-based quantum computers, (iii) quantum computers and components as well as software, and technology that can be used in the development and maintenance of quantum computers. To ensure that these controlled items are not used for purposes "contrary to U.S. national security or foreign policy," a license requirement has been imposed. However, a new License Exception Implemented Export Controls (LE IEC)[173] is possible when BIS determines that a country has implemented comparable controls on an item. In EU, the Member States that implemented comparable trade controls, supplementing the EU Regulations 2021/821 are listed in Table 5. As a result, license exemption for those items is available for Finland, Italy, and Netherlands, and partially available (i.e., only on some items) for Denmark, France, Germany, Slovenia, and Spain, leading to a fragmentation of EU under the US trade control measures.

Table 5 National rules on quantum related items, supplementing the EU Regulation (EU) 2021/821 on export control of dual-use items[174]

EU Member State	CMOS integrated circuits and parametric signal amplifiers operating at very low temperatures	Cryogenic cooling systems, component and wafer probing equipment	Materials consisting of certain silicon (Si) or germanium (Ge) isotopes	Quantum computers and related components
Denmark	√			√
Finland	√	√	√	√
France	√			√
Germany	√	√		√
Italy	√	√	√	√
Netherlands	√	√	√	√
Slovenia	√			√
Spain				√

Source: table of the US license exception implemented export controls (LE IEC) modified 2 December 2024[175] in relation to the BIS rule on "Implementation of Controls on Advanced Technologies Consistent With Controls Implemented by International Partners"[176]

Export control restrictions are also leading to increased tension and retaliation. For instance, in the growing tension for export control on semiconductors, in December 2024 and in February 2025 China retaliated by imposing additional export restrictions on critical materials (such as rare earth materials), in addition to germanium and gallium

172 Commerce Control List Additions and Revisions; Implementation of Controls on Advanced Technologies Consistent With Controls Implemented by International Partners, A Rule by the Industry and Security Bureau on 09/06/2024, available at: https://www.federalregister.gov/documents/2024/09/06/2024-19633/commerce-control-list-additions-and-revisions-implementation-of-controls-on-advanced-technologies

173 US license exception implemented export controls (IEC) at https://www.bis.gov/iec

174 Regulation (EU) 2021/821 of the European Parliament and of the Council of 20 May 2021 setting up a Union regime for the control of exports, brokering, technical assistance, transit and transfer of dual-use items, https://eur-lex.europa.eu/eli/reg/2021/821/oj/

175 BIS, license exception implemented export controls (IEC) eligible items and destinations, dated 2/12/2024, accessible at: https://www.bis.gov/iec

176 US Federal Register, Commerce Control List Additions and Revisions; Implementation of Controls on Advanced Technologies Consistent With Controls Implemented by International Partners, dated 9/6/2024, accessible at: https://www.federalregister.gov/documents/2024/09/06/2024-19633/commerce-control-list-additions-and-revisions-implementation-of-controls-on-advanced-technologies

which are under the Chinese export restrictions since July 2023.[177] Some of these materials are also use for quantum applications. A similar case is related to the export control of synthetic diamond (see below for an in-depth view).

The case of export control on synthetic diamond

Nitrogen-vacancies (NV) in diamond constitute a very interesting quantum platform, which can find application in quantum computing (in a rather long-term technology evolution scenario), quantum communications (as memories for quantum repeaters) and quantum sensing. In this last area, some products are reaching the market, e.g. magnetometric imaging devices to be used in the semiconductor industry for chip quality inspection.[178]

The **manufacturing process of quantum-grade diamond is very demanding and its market is still small**, so the pool of commercial suppliers is extremely limited: in Europe, it is dominated ElementSix of the UK, which is part of the DeBeers group. Besides quantum, diamond has well-established applications in several fields where its ultra-hardness is exploited, and as a substrate for semiconductor manufacturing for its thermal transport properties.

Its commerce is being progressively restricted by the US and China. The first step was taken by the US in 2022 in the context of the "Chips act", when the **US Bureau of Industry and Security (BIS) issued an "interim final rule" that established new export controls[179] on synthetic diamond**, asserting that when used as a substrate for ultra-wide bandgap semiconductors it allows them to work under more severe condition (such as at higher voltages or higher temperatures), enabling the manufacturing of devices with enhanced military potential.

In what was widely considered a tit-for-tat move, between August and December 2024 **Beijing introduced stringent export restrictions**,[180] with permits required for any overseas sales of "ultra-hard materials such as diamond window components, six-sided top press equipment, and related technology for manufacturing synthetic single crystals like artificial diamonds", and controls introduced also on upstream raw materials.

Most diamond made in China is manufactured with a High-Temperature High-Pressure process starting from graphite, which is on the EU's strategic raw materials list. Conversely, higher quality diamond used in the semiconductor industry and for quantum applications is typically grown with chemical vapour deposition (CVD), starting from highly purified precursor gases and using equipment available from Japanese, French and German suppliers. Supported also by EU funding, **several European startups targeting the manufacturing of quantum-grade NV-doped diamond are emerging**.[181]

The ability to export worldwide would be crucial for their economic viability, and trade control measures will have to trade-off market sustainability with security concerns. In this scenario, a common EU position will be necessary to effectively counterbalance the trade tensions between US and China.

177 See for instance the following briefs summarizing the increasing export control restrictions by China: 1) "Beyond Rare Earths: China's Growing Threat to Gallium Supply Chains" by Aidan Powers-Riggs, Brian Hart, Matthew P. Funaiole, Scott Thomsett, Simon Zieleniewski, and Tim Rose of the Center for Strategic and International Studies (CSIS), available at: https://www.csis.org/analysis/beyond-rare-earths-chinas-growing-threat-gallium-supply-chains; 2) "Chinas's use of export controls" by the International Institute for Strategic Studies (IISS), available at: https://www.iiss.org/online-analysis/charting-china/2025/02/chinas-use-of-export-controls/

178 For instance, see https://qnami.ch/

179 BIS, "Commerce Implements New Multilateral Controls on Advanced Semiconductor and Gas Turbine Engine Technologies," 12 August 2022, available at: https://www.bis.doc.gov/index.php/documents/about-bis/newsroom/press-releases/3116-2022-08-12-bis-press-release-wa-2021-1758-technologies-controls-rule/file;
See BIS, "Commerce Implements New Multilateral Controls on Advanced Semiconductor and Gas Turbine Engine Technologies," 12 August 2022, available at: https://www.bis.doc.gov/index.php/documents/about-bis/newsroom/press-releases/3116-2022-08-12-bis-press-release-wa-2021-1758-technologies-controls-rule/file;
and the Federal Register, "Implementation of Certain 2021 Wassenaar Arrangement Decisions on Four Section 1758 Technologies," 15 August 2022, available at: https://www.federalregister.gov/documents/2022/08/15/2022-17125/implementation-of-certain-2021-wassenaar-arrangement-decisions-on-four-section-1758-technologies

180 DIGITIMES Asia, "China tightens antimony exports, raising supply concerns," 19 August 2024, available at: https://www.digitimes.com/news/a20240816PD214/china-ic-manufacturing-materials-exports-production.html; https://www.chinadaily.com.cn/a/202501/21/WS678f0a43a310a2ab06ea845d.html

181 For instance, Diatope (DE) https://diatope.com/

Points for debate:

- How to ensure that the EU does not get fragmented in a time of growing trade controls? How can the EU collaborate with other countries, adopting science diplomacy[182]?

182 Merics, "China's long view on quantum tech has the US and EU playing catch-up," available at: https://merics.org/en/report/chinas-long-view-quantum-tech-has-us-and-eu-playing-catch

5 Recommendations for key decisions to be taken

5

Based on the data and observations presented above, we would like to propose a list of what we believe to be the main decisions which need to be taken. They are rather more general than the detailed points for debate mentioned in the previous chapters but somewhat more specific than the high-level plans contained in the Quantum Europe Strategy.

For quantum communications:

- Decide how can the investment in EuroQCI best be realised, e.g., to ensure the required level of performance and security, to scale the network, to miniaturise the quantum devices.
- Decide if and which technology gaps identified for EuroQCI can be fed back to the Quantum Flagship as topics for research.
- Decide the future of EuroQCI: Is it mainly a security asset? Is it mainly a means to support the growth of the EU quantum industry? Will its long-term significance be as a stepping-stone towards quantum communications for all the users? What future investments will be needed? How to enhance the synergies with other quantum technolo-gies research initiatives (such as the ESA programme)?
- Decide on the standards for quantum key distribution (QKD) and post-quantum cryptography.

For quantum computing and simulation:

- Decide on the priorities for quantum computing research and development, including the development of quantum algorithms and software. Are there further implications for cybersecurity beyond the known threats?
- Determine the best approach for supporting the development of quantum computing hardware, including hybrid architectures, quantum processors, and simulators.
- Decide on the priorities for quantum simulation research and development, including the development of quantum simulators and software. Can the EU start building a strategic independence in the sector?
- Determine the best approach for supporting the development of quantum simulation hardware, including quantum processors and simulators.

For quantum sensing and metrology:

- Decide on the priorities for quantum sensor research and development, including the development of quantum sensors for navigation, timing, and spectroscopy. Priorities should consider the real quantum advantage, the potential for large civil market, the strategic importance for defence
- Determine the best approach for supporting the development of quantum metrology and clock technologies, including the development of quantum clocks and timing systems. Is there a case to reinforce public support for this area, not only by funding development but also by ensuring an EU market for EU-made devices important for critical applications?
- Determine what will be the metrology needs of the emerging quantum industry and whether quantum devices can help metrology by shortening calibration chains.

For funding and investment:

- Decide on the level of funding and investment needed to support the development of quantum technologies, including the trade-off between fundamental research and quantum applications, between research and development, infrastructure, and education.
- Determine the best approach for allocating funding and investment across different areas of quantum technology, including computing, simulation, sensing, and communication.

For regulation and standardisation:

- Decide on the regulatory framework for quantum technologies, in particular for security.
- Determine the best approach for developing and implementing standards for quantum technologies, including standards for interoperability and compatibility.

For International Cooperation:

- Decide on the level of international cooperation needed to support the development of quantum technologies, including cooperation on research and development, standards, and regulation, considering also the dual use of quantum technologies.
- Determine the best approach for collaborating with international partners, including the development of joint research initiatives.

These key decisions for recommendations aim to provide a comprehensive framework for supporting the development of quantum technologies in the EU.

6 Conclusions

6

The claim for the **"second quantum revolution"** is that it enables the exploitation of the peculiar properties of individual quantum systems to attain progress in computation, communications, and sensing which would be otherwise unattainable. Its potential to transform multiple sectors of the global economy is vast, spanning a very wide range of sectors including cybersecurity, chemical and materials engineering, pharmaceuticals and life-sciences, environmental monitoring, finance, mobility, aerospace and defence.

To become useful in practical instances, quantum technologies need to overcome diverse and significant challenges. To give an example, quantum computing has already been theoretically demonstrated to be transformative for certain tasks, but it requires huge progress in the state of the art for practical applications and real advantages. Second, for some applications, like quantum key distribution, there are severe acceptance issues linked to the break with existing paradigms. Third, the cost vs benefits balance may prove unfavourable, since progress is also to be expected in solutions based on non-quantum technologies.

At this stage, the extent to which each quantum technology will deliver useful applications varies, as does the timeframe for delivery, and, for some, they are difficult to predict. Some quantum technologies will remain confined to a limited number of high-end scientific applications which require the best possible instruments, to be used e.g. for metrological applications, fundamental physics, or simulations of peculiar quantum phenomena: they will contribute only indirectly to our progress and will likely remain heavily dependent on public support. For other quantum technologies, the direct economic gains of the enabled applications will ensure a self- sustained cycle of innovations by high-tech entrepreneurs funded also by private investors, which over time will embed new products and services in the market, with an immediate impact for economic and scientific progress. Given the wide range of developments which are taking place under the quantum technologies label, one may expect varied outcomes between these two extremes.

Despite the challenges, the **quantum technology sector has undergone remarkable growth in the last decade**, which is clearly marked by a surge in investments and firm creation. The comprehensive analysis of the current state of the sector has yielded several key findings, highlighting both the opportunities and challenges faced by the industry. Notably, the quantum technology sector has been expanding rapidly since 2017, with over 440 companies identified, primarily operating in quantum computing (64%), post-quantum cryptography (15%), quantum sensing (11%), and quantum key distribution (10%). This growth is fuelled by the significant economic potential of quantum technologies, with some market reports projecting a market size of USD 70 bn- USD 173 bn by 2040, and potential gains of up to USD 2tn by 2035 in industries such as chemicals, life sciences, finance, and mobility.

Europe boasts a long tradition of excellence in quantum research, with a high record of scientific publications and multiple Nobel Laureates in Physics awarded for discoveries in quantum, second only to the USA. The EU is home to a substantial share of quantum companies, accounting for 32% of the total, and 36% of QKD technologies, where the EU is at the forefront. However, despite this impressive presence, the **EU only accounts for 6% of global patenting**, with China dominating the field, owning 46% of global patents, followed by the US with 23%. **EU companies are generally younger and smaller** than those in other jurisdictions, but they are more open to collaborating with non-European partners for patenting.

The patent landscape is currently led by US and Chinese giants, such as Microsoft, Google, Intel, Baidu, Alibaba, and Huawei, which possess the infrastructure, economic resources, and industrial capability to reap the benefits of the quantum revolution, potentially foreclosing other competitors. This underscores the need for additional action in the EU to foster market applications of the knowledge developed in Europe and provide incentives to the industrial base to experiment and capitalise on new developments in quantum.

To address this challenge, **the EU invested over EUR 2bn in quantum technologies by the end of 2024, through various initiatives**, including the Quantum Technology Flagship, funded primarily through Horizon 2020 and Horizon Europe. This is in addition to Member State national programmes, which collectively are several times larger. **Furthermore, while EU companies invested €1 billion of venture capital in the technology, EU quantum companies received €862 billion** The funding programmes, in place in the EU for at last ten years, are yielding noticeable results not only in terms of scientific output but also in the formation of an ecosystem of enterprises which are developing quantum–enabled applications and services. In this regard, a major role is being played also by infrastructural deployment spanning all the continent, such as the EuroQCI and the quantum computers of the HPC-Joint Undertaking. Directly or indirectly, the EU quantum enterprises are to a large extent subsidised by public money. The data on companies and finance in Chapter 3 are evidence in support of the view stated in the Quantum Europe Strategy that the ecosystem in Europe, although promising, remains very fragile and decisive steps are needed to strengthen it.

Overall, the EU is well-positioned to play a key role in the development of quantum technologies, with its strong research and innovation ecosystem, and significant investments in the sector. To maintain its position and move from the potential of quantum technologies to real world applications, an EU- wide endeavour is necessary, because

i. a very large-scale effort is needed

ii. only the entire EU represents a market large enough to entice manufacturers

iii. only a coordinated action at continental scale can match our competitors (USA and China).

The data and analysis presented in this report indicate also very clearly that **the current EU quantum technology programme is fragmented**, and the new Quantum Europe Strategy has the potential to integrate the efforts, driving the innovation and the development in strategic directions. Moreover, it is essential that the Quantum Europe Strategy lays down actions to remove the obstacles which prevent Europe competing as a single player.

To remain competitive in the global market, the EU must continue to invest in research and development, and encourage collaboration and cooperation between companies, research institutions, and governments as follows:

- **Develop practical solutions**: Translate research into concrete quantum technologies and algorithms that address specific industry challenges, such as optimisation, simulation, or cryptography., increasing the TRL of the solutions.
- **Demonstrate value**: Showcase the benefits and value of quantum technology to users, highlighting its potential to improve efficiency, reduce costs, and enhance decision-making.
- **Build a strong ecosystem**: Foster a vibrant ecosystem that brings together researchers, industry leaders, and investors to drive innovation, entrepreneurship, and growth in the quantum sector.
- **Invest in talent and infrastructure**: Continue to invest in education, research, and infrastructure to support the development of quantum technology and attract top talent to the field. Do it in a coordinate manner within Member States to avoid "subsidy shopping" by companies.
- **Consolidate the investments** at national and EU level in key strategic technologies or directions, reducing the fragmentation of programmes where possible.
- **Preserve EU technology edge** with a wide range policies and legal instruments coordinated with Member States. The Quantum Europe Strategy states the necessity of promoting intellectual property protection mechanisms to ensure strategic control over key innovations and prevent the outflow of critical assets.
- **Drive standardisation** of solutions and enabling technologies to reduce costs.
- **Develop an EU supply chain and production capabilities**, in particular for the quantum applications related to space, defence and security.

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List of abbreviations and definitions

Abbreviations	Definitions
AI	Artificial Intelligence
CAI	Cold atom interferometry
CAGR	Compound annual growth rate
CEF	Connecting Europe Facility
CEN	Comité européen de normalisation
CENELEC	Comité européen de normalisation en électronique et en électrotechnique
CMC	Calibration and measurement capabilities
CNES	Centre national d'études spatiales
CNRS	Centre national de la recherche scientifique
COST	European Cooperation in Science and Technology
CSA	Coordination and support action
CSAC	Chip-scale atomic clock
DEP	Digital Europe Programme
DH	Diffie-Hellman key exchange
DLR	Deutsches Zentrum Für Luft und Raumfahrt
DARPA	Defense Advanced Research Projects Agency
EC	European Commission
ECC	Elliptic Curve Cryptography
ECC-DH	Elliptic Curve Cryptography Diffie-Hellman key exchange
ECSEL	Electronics Components and Systems for European Leadership
EDA	European Defence Agency
EDF	European Defence Fund
EIB	European Investment Bank
EIC	European Innovation Council
EMN-Q	European Metrology Network- quantum technologies
EMRP	European Metrology Research Programmes
EQF	European Qualification Framework
ERA	European Research Area
ERC	European Research Council
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
ETSI	European Telecommunication Standards Institute
EU	European Union
EUCC	EU Cybersecurity Certification Scheme on Common Criteria
EuroHPC-JU	European High-Performance Computing Joint Undertaking
EuroQCI	European Quantum Communication Infrastructure
EURAMET	European Association of National Metrology Institutes
FET	Future and Emerging Technologies
GNSS	Global Navigation Satellite System
GSM	Global System for Mobile Communications
GSMA	GSM Association

HPC-JU	High Performance Computing Joint Undertaking
IEC	International Electrotechnical Commission
IETF	Internet engineering taskforce
IRIS2	Infrastructure for Resilience, Interconnectivity, and Security by Satellite
ISO	International Standards Organisation
IT	Information technology
ITSEF	Information Technology Security Evaluation Facility
ITU-T	International Telecommunication Union – Standardization
JUICE	Jupiter Icy Moons Explorer
KDT-JU	Key Digital Technologies Joint Undertaking
MIT	Massachusetts Institute of Technology
MSCA	Marie Skłodowska-Curie Actions
NASA	National Aeronautics and Space Administration
NISQ	Noisy intermediate-scale quantum
NIST	National Institute of Standards and Technology
NMI	National metrology institutes
NV	Nitrogen-vacancy
PIC	Photonic integrated circuit
PQC	Post-quantum cryptography
QC	Quantum computing
QKD	Quantum key distribution
QRNG	Quantum random number generator
QS	Quantum sensing
QT-CCI	Quantum Technology Cross-Cutting Initiative
QUCATS	Quantum Flagship's Coordination and Support Action
QUESS	Quantum Experiments at Space Scale
QuIC	European Quantum Industry Consortium
RF	Radio Frequency
RSA	Rivest, Shamir, Adleman cryptosystem
SAB	Strategic Advisory Board
SAGA	Security and Cryptographic Mission
SDO	Standards development organisation
SI	Système International
SME	Small or medium enterprise
SRIA	Strategic Research and Industry Agenda
STEM	Science, technology, engineering, mathematics
STEP	Strategic Technologies for Europe Platform
TRL	Technology readiness level
VC	Venture capital

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