QUANTUM TECHNOLOGIES

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INTESA SANPAOLO INNOVATION CENTER

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Daniele Borghi
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Davide Corbelletto - Intesa Sanpaolo
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Quantum technologies have the potential to change the rules of the game, leading to a redefinition of business models, value chains and competitive positioning.

These technologies represent not only scientific progress, but also a strategic asset of utmost importance for the competitiveness of economic systems and the technological sovereignty of nations. The race to quantum computing, sensors and quantum communications is already defining new geopolitical and industrial equilibriums, calling on businesses, institutions and scientific communities to make a joint commitment.

Alongside the opportunities, there are responsibilities that cannot be ignored. The adoption of these technologies must be developed within a framework of sustainability, fairness and respect for ethical values. When properly harnessed, quantum power can contribute to ecological transition, efficient resource management and the construction of a more resilient and inclusive society.

Our task is to accompany this revolution with strategic vision and responsibility, while ensuring agility and speed of execution.

The report we present analyses the ecosystem and the market, the main players and emerging start-ups, the level of maturity of the technologies, use cases and industrial applications, providing a clear summary of the prospects and challenges that will shape the future of quantum technologies.

Viviana Bacigalupo
General Manager Intesa Sanpaolo Innovation Center

Stefano Buscaglia
General Manager LINKS Foundation

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Foreword

The scientific understanding of quantum effects is not new. The physicists Max Planck, Albert Einstein and others developed their theories 125 years ago and this year we are celebrating the United Nations Year of Quantum due to the 100th anniversary of quantum mechanics. But only in recent years the understanding and technology was developed, how to control quantum effects in a way, that they can be used in a practical application, like sensing, communication or computing.

Today, first quantum based sensors are in use in various industrial applications and in health care. The advantages of quantum communication are also used in first security related applications. Although quantum computing, where we expect the biggest commercial potential, only started to find its way out of research labs, universities and computer centers. Nevertheless, companies, like IQM, are already producing computers in batches and are shipping their products to first-movers in the quantum application arena. Quantum computing as a service is also available through cloud applications. Those solutions are used to develop new algorithms and for training and education of young scientists.

Relevant players are in the race for the first applications which create more commercial value than classical digital systems. There will be a market with more than one player, but to be profitable, it is important to be in the market early and offer relevant commercial solutions soon.
The relevance of quantum computing is not only defined by its ability to solve complex algorithms through parallel computing in a very short time, it will as well solve computing problems, which cannot be solved by any classical computers in a realistic timeframe. Some of those algorithms would take millions of years even on our biggest supercomputers or would require more transistors than we have atoms in the universe.

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The application of artificial intelligence will benefit from quantum computing as well, the needed energy and time used by AI applications will be dramatically reduced.
Currently, we see a global competition in the development of quantum systems between China, US, Japan and Europe, which can be characterized by high investment. While about the activities and investment in China not much information is available, we see a strong will in Japan and Europe to invest and to develop some independence from US based companies.
The evolution of quantum computing in Europe has been shaped by a coordinated mix of research programs, public and private investments, and regulatory initiatives. Since the launch of the EU's Quantum Flagship program in 2018, Europe has built a vibrant ecosystem around quantum technologies, enabling companies to move from early-stage research into commercial expansion. The Quantum Flagship has been complemented by major EU-level initiatives such as the EuroHPC program, which funds six hosting sites for quantum computers, and the EU Chips Act, which seeks to strengthen Europe's capabilities in quantum chip technologies through a combination of public and private investment. More recently, the European Commission announced its Quantum Europe Strategy, which is expected to culminate in the Quantum Act in 2026, providing a comprehensive legislative framework for the sector.

Alongside these EU-wide programs, national governments have played a crucial role by funding large-scale projects. Finland, for instance, committed €20.7 million and €70 million to VTT's 5–20–50 and 300-qubit computer projects, while Germany's Federal Ministry of Education and Research (BMBF) has invested €40 million in integrating a quantum computer into the SuperMUC-NG supercomputer at the Leibniz Supercomputing Centre in Munich. These efforts reflect a deliberate strategy to anchor quantum computing development in Europe and position the region as a competitive player globally.

Early involvement of state investors such as Tesi, Finnish Industry Investment Ltd, and the European Innovation Council (EIC) are significant for the sector, as they signal both technological credibility and long-term policy commitment. Public capital helps bridge the so-called "valley of death" between fundamental research and commercial viability, giving startups the time and resources to generate revenue before later-stage venture investors step in. Compared with other regions, Europe's strength lies in its strong policy frameworks and public-private alignment, though it still faces challenges in scaling as quickly as its competitors.

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The broader ecosystem benefits from Europe's strong academic foundations, a vibrant startup scene, and public-private collaborations that provide shared infrastructure and early customers. Upcoming policies such as the Quantum Act will be decisive in shaping both funding as well as economic security, particularly given the dual-use nature of quantum technologies. The success of Europe's ecosystem will therefore depend on how effectively companies and governments work together to balance innovation with national security concerns.

As the European quantum industry matures, it is likely to have a profound impact on innovation and competitiveness at both the regional and global level. Europe's model, which emphasizes strong research foundations, early public investment, and structured collaboration, has positioned it as a leader in shaping the global quantum landscape. If it can continue to channel sufficient private investment and accelerate commercialization, Europe can remain a central player in the global race for quantum technologies.

Reinhold Achatz
IQM Quantum Council Member
Chairman of the Board and President at the International Data Spaces Association (IDSA), formerly CTO and Head of Corporate Function Technology, Innovation, and Sustainability at ThyssenKrupp

Jan Götz
Co-CEO & Co-founder IQM Finland Oy

Heinrich von Pierer
IQM Quantum Council Member
Member of supervisory boards at various companies, formerly CEO and Chairman of Siemens AG

Francesco Profumo
IQM Quantum Council Member
President of Isybank, formerly President of Compagnia di Sanpaolo, Minister of Education, and President of the National Research Council (CNR)

Viviane Reding
IQM Quantum Council Member
Member of the European Parliament, formerly Vice President of the European Commission

Axel Thierauf
Quantum physicist and seasoned venture capital investor
Early investor and Chairman of the Quantum Council at IQM Finland Oy

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Overview

Technologies commonly referred to as quantum technologies derive their name from the discipline known as **quantum theory or quantum mechanics**, as they are based on the functioning of matter at the subatomic and particle level described by this physical model, which was conceived in the early 20th century.

Unlike classical physics, which deals with describing the behaviour of the macroscopic world – from the laws of electromagnetism to the theory of general relativity – quantum theory focuses instead on interpreting the working of the microscopic world, which sometimes exhibits behaviour that is counterintuitive compared to the physical experience of the world to which we are commonly accustomed.

1.1 The Two Quantum Revolutions

Over the last century, humanity has witnessed two revolutions linked to the world of quantum physics applications, with significant technological implications.
While the first of these revolutions changed the interpretation of nature's behaviour, the second is changing the way we interact with it.

The first quantum revolution: a new interpretation of the microscopic world

The first quantum revolution began in the early 1900s, when physicist Max Planck proposed the idea that energy is not continuous, but rather discrete and separated into indivisible units called "quanta".

A few years later, in 1905, drawing inspiration from this very idea, Albert Einstein was able to scientifically justify the occurrence of the so-called photoelectric effect (i.e. the conversion of light into energy), hypothesising that light, in addition to being representable as a wave, also takes on the characteristics of a particle (the photon), a discovery that earned him the Nobel Prize in Physics in 1921.

From then on, scientists such as Niels Bohr, Werner Heisenberg, Erwin Schrödinger, Wolfgang Pauli, Paul Dirac and others laid the foundations of quantum mechanics, a theory capable of explaining some **seemingly counterintuitive behaviour** of matter at the subatomic level, including:

- **Wave-particle duality**: elementary particles, such as electrons and photons, exhibit both wave and corpuscular properties
- **Superposition:** an elementary particle can exist simultaneously in a combination of multiple states, each with a certain probability
- **Indeterminacy**: it is not possible to know simultaneously and with absolute precision certain pairs of properties of an elementary particle, such as, for example, its position and velocity
- **Entanglement**: elementary particles can "interconnect" (or become entangled), so that there is a correlation between their states that is preserved regardless of the distance between them

Out of these new theoretical assumptions, a first series of technological innovations emerged that proved decisive for the modern world: from silicon transistors, the basis of microprocessors, to lasers for accurate measurement of distances, also at an astronomical level, to magnetic resonance imaging used in diagnostics and fibre optics, on which the World Wide Web is based today.

In summary, the first quantum revolution enabled humanity to shed light on the fundamental structure of nature and to develop applications capable of exploiting quantum principles in an innate way, without directly controlling them.

The second quantum revolution: how to manipulate quanta

At the end of the 20th century, a second quantum revolution began, marking a significant leap forward not only in terms of understanding, but also in the control of the intrinsic behaviour of the subatomic world.
Nowadays, we no longer just take advantage of quantum phenomena in a pretty much spontaneous way, but we are getting better at manipulating them directly and precisely.

As a result of recent advances in engineering, it is possible to isolate and **control individual particles**, such as electrons and photons, preserving their quantum properties long enough to use them in a conscious and programmed manner.

This second quantum revolution actually paved the way for three large technology families known as **quantum technologies**:

- **Quantum Computing**, which encompasses both the creation of a new type of computer (Quantum Computer) based on the laws of quantum mechanics and the writing of new algorithms designed to be implemented and executed on this new type of machine, offering advantages in terms of both calculation times and the accuracy of expected outputs compared to traditional computers
- **Quantum Communication**, which uses entanglement to create new, ultra-secure communication protocols, while ensuring that any unauthorised interception attempts are immediately detected
- **Quantum Sensing**, which gives rise to sensors capable of measuring physical quantities such as magnetic fields, gravitational variations or infinitesimal temporal variations with extremely high precision, with applications in medicine, geology, navigation and fundamental physics

In summary, while the first quantum revolution allowed humanity to appreciate some of the spontaneous potential arising from the unique physical properties that characterise the microscopic world, the second is providing the tools to build new technologies, based on a better understanding and control of the natural phenomena governed by these principles.

Briefly analysed below, the three quantum technologies will be explored in more detail in Chapter 3.
For each technology, the main industrial sectors in which it is currently applied or most likely to be applied are also listed. An in-depth examination of industrial applications is the focus of Chapter 4.

1.2 Quantum Computing

Quantum computing is a computing model that exploits the laws of quantum mechanics to solve problems that are too complex, in terms of solution time, available computing space or energy resources, to be effectively handled by traditional computing architectures.
Unlike conventional computing, which uses the minimum unit of information known as a bit (which can take on the value of either 0 or 1), quantum computing uses **qubits** (quantum bits), which have significantly different properties.

The combined use of the three properties of qubits allows quantum computers to simultaneously process many solving scenarios and thus achieve better results than traditional computers, both in terms of speed and accuracy of output, while reducing computational resources and therefore the overall energy required for computation.

Types of qubit

Qubits can be engineered in many different ways, each with its own advantages and technical challenges:

- **Superconductive qubits**: these are made from superconducting materials cooled to temperatures close to absolute zero. They currently represent one of the most easily scalable platforms, to the extent that they form the technological solution underlying the quantum computers of companies such as IBM, Google, Amazon, D-Wave, Rigetti and IQM
- **Trapped-ion qubits**: these are made with ionised atoms suspended in electromagnetic traps and manipulated using laser pulses. Companies such as Quantinuum (a consortium that also includes the multinational Honeywell) and IonQ are investing heavily in this technology, which is valued for its reliability and consistency

QUBITS PROPERTIES

The functioning of qubits is based on the application of three fundamental physical principles:

SUPERPOSITION

A qubit, in addition to being in a well-defined basic physical state (0 or 1), can also be in one of an infinite number of configurations resulting from the combination of the basic states, each with a certain probability (for example, 0 and 1 simultaneously at 50%). This allows for an increase in the overall computational space available with the same number of elementary data processing units available (i.e. qubits instead of bits)

ENTANGLEMENT

Two or more qubits can become entangled in such a way that a change in the state of one immediately affects the other, regardless of the distance between them. This particular type of bond allows information to be encoded and transmitted much more efficiently and is also commonly known as "action at a distance"

INTERFERENCE

A qubit, as an elementary quantum system, combines corpuscular and wave characteristics, and is therefore subject to the physical principle of interference, which is exploited to amplify the probabilities of finding the correct answer to a problem encoded in it, destructively limiting the incorrect ones

- **Photonic qubits:** as the name suggests, qubits correspond to photons, which are used to encode and process information. In addition to being more stable and resistant to surrounding noise, photons are also ideal for long-range communication. It is no coincidence that promising start-ups such as PsiQuantum, funded by the US government among others, and Xanadu are following this approach
- **Neutral atom qubits:** these are made from non-ionised atoms, cooled and controlled using appropriate optical instruments. They strike a good balance between scalability and consistency. Among the companies pursuing this approach are QuEra in the US and Pasqal in Europe
- **Silicon spin qubits**: in this case, the qubits correspond to the spins of electrons confined in semiconductor structures, similarly to what happens in so-called quantum dots, which act as pixels in QLED TVs. The main advantage of this approach is its substantial compatibility with ordinary chips, which are also silicon-based. Unsurprisingly, Intel is among the companies investing most heavily in this area
- **Topological qubits**: the idea behind this technological solution is to use exotic quasiparticles (non-Abelian anyons) to represent qubits. Microsoft is the main proponent of this approach that, while promising intrinsic fault tolerance, is still in the theoretical research phase and has not yet been tested
- **Nitrogen-Vacancy Centre**: qubits correspond to point defects in the crystal lattice of a diamond, where a nitrogen atom replaces a carbon atom near a vacancy. Although this technology has the advantage of providing high stability even at room temperature, scalability depends on the number of impurities in the diamond. Companies such as Quantum Brilliance and SaxonQ are exploring this approach, particularly with a view to selling small quantum computers for installation in data centres

Each of the methods for creating qubits described above is evaluated on the basis of four key properties:

- **Scalability**: possibility of increasing the number of qubits without significantly increasing the size of the quantum chip that contains them, while maintaining the overall reliability of the system
- **Speed**: ability to increase the system's calculation frequency in order to ensure a greater number of operations performed per unit of time
- **Fidelity**: probability that the system will remain accurate in performing physical/logical operations on qubits without incurring failures/errors
- **Coherence**: ability to extend the time during which qubits retain their characteristic quantum properties, which are by nature ephemeral as they are subject to various types of external perturbations (e.g. magnetic or thermal)

The main challenge is to increase all of the above dimensions without the growth of one negatively affecting the others, in order to achieve reliable and useful processing architectures on a large scale.

Industrial applications

Although the technology is still in its infancy, its potential is already apparent in many areas:

- **Pharmaceutics and materials science**: accurate simulation of chemical compounds and complex materials. This can accelerate the discovery of new medicines, catalysts and complex molecular structures, a task in which even the most powerful classical computers prove inefficient
- **Finance**: investment portfolio optimisation, risk management, predictive analytics and stochastic simulations. Quantum computing can drastically reduce the time required for highly complex analyses, while increasing the accuracy of results
- **Logistics and transport**: solving problems such as better route planning, resource allocation or strategic planning, potentially in real time
- **Energy**: modelling of complex systems such as those designed to prevent failures in electrical networks, improving efficiency and ensuring operational stability
- **Artificial Intelligence**: some machine learning applications could benefit from quantum approaches both to accelerate the training of supervised models and to improve the quality of predictions of unsupervised ones or the choices made by an agent trained by reinforcement learning

In addition to promising a significant reduction in processing time when solving certain problems and a higher quality of output solutions, in some cases quantum computing even makes it possible to tackle **problems that classical computers cannot manage**, which, unfortunately, can also prove to be negative.

A potential threat to cryptography

These inaccessible problems include the factorisation of integers with an arbitrary number of digits into prime numbers.

The well-known RSA public key cryptographic protocol is based on the impossibility for a traditional computer to perform this decomposition in a reasonable amount of time. Since 1977, the year it was conceived, the protocol has helped to protect, among other things, web communications and financial transactions. However, as early as 1994, computer scientist Peter Shor devised a quantum algorithm that allows even very large integers to be broken down into prime factors in exponentially less time than the best classical technique. Therefore, a sufficiently powerful quantum computer could **break current cryptographic protections**, threatening much of global digital security and necessitating replacement with newly developed cryptographic systems that are resistant to this type of attack, known as Post-Quantum Cryptography (PQC).

A Survey on Post-Quantum Cryptography: State-of-the-Art and Challenges

1.3 Quantum Communication

Quantum communication is a technology that encompasses a set of quantum telecommunication systems that primarily leverage the principle of entanglement to create essentially secure data transmission channels which, for certain applications, are more efficient than traditional information exchange systems.

The new frontier of inviolable communications

Compared to traditional communication protocols, this type of system guarantees intrinsic security (i.e. guaranteed by the medium used for transmission rather than by a software algorithm), the ability to detect any interception attempts, and better transmission capacity for the same amount of time and bandwidth available.

Unlike traditional data transmission systems (where data travels from sender to recipient encoded in the form of binary electrical pulses), **quantum communication systems use photons**, which allow the exchange of information even in superposition states (thus increasing the amount of data sent per unit of time, given the same transmission capacity of the channel used) and pieces of information not locally correlated (i.e. information that can also be sent non-sequentially on different channels, while maintaining the same information content).

In an increasingly interconnected world subject to growing cyber threats (including those potentially posed by future quantum computers, as discussed above), classical cryptography methods based on difficult mathematical problems could become vulnerable.

Besides Post-Quantum Cryptography, which is a logical solution to the problem, **Quantum Key Distribution** (QKD) is a possible strategy for secure and physically guaranteed data transmission.

Quantum Key Distribution is a technique that allows two interlocutors (traditionally called *Alice*, the sender, and *Bob*, the recipient) to exchange a secret key by exploiting the properties of quantum mechanics. The first protocol designed for this purpose is BB84, named after its creators Bennett and Brassard, who proposed it in 1984. This protocol ensures that any attempt to intercept the key will result in the inevitable alteration of the key itself, thus rendering the intercepted information unusable to the attacker and at the same time revealing the unauthorised attempt of theft to the recipient of the communication.
More recent and efficient developments of the BB84 protocol are the Ekert protocol and so-called Quantum Teleportation, which employ more advanced forms of entanglement between the photons used for key transmission.

Entanglement and teleportation in quantum key distribution for secure wireless systems

The QKD protocol does not directly transmit messages, but rather provides a set of inviolable encryption keys to be used for exchanging data over conventional channels. This system has already been tested in various real-world contexts, including via satellite repeaters and fibre optic channels, paving the way for a future distributed quantum communication network (Quantum Internet).

Another advantage of using quantum communications lies in the so-called **Superdense Coding**, a technique that allows **multiple bits of information to be transmitted simultaneously for each photon** used in the transmission.

In a classic communication, a single bit transmits at most one binary piece of information (0 or 1). Instead, with superdense coding, the sender can send two classical bits using a single photon, if this is entangled with another photon already held by the recipient.
This mechanism increases communication efficiency and shows how entanglement can be exploited to maximise the transmission capacity of channels.
When combined with the right network infrastructure, it is possible to create high-density, ultra-low latency hybrid communication systems, which are useful in contexts with particularly demanding transmission requirements.

Industrial applications

Already in the short term, quantum communication is one of the most promising areas in terms of tangible applications.

Sectors that can benefit the most include:

- **Defence and security**: military, governmental and institutional intelligence intrinsically protected from even sophisticated attacks, including those perpetrated by sufficiently powerful quantum computers in the future
- **Financial services**: security of banking transactions and sensitive communications concerning customers exchanged between central banks, financial institutions and insurance companies
- **Telecommunications and critical infrastructure**: creation of quantum networks to ensure greater communication efficiency and substantial security for data transmitted on an international scale
- **Healthcare**: secure sharing of medical data and confidential information relating to clinical or pharmaceutical research
- **Cloud and datacentres**: improvement of transmission capacity and integrity of information exchanged in client-server mode, particularly in multi-tenant and distributed contexts

Despite still being an evolving technology, especially in the field of free space communication, concrete implementations already exist in which quantum communication has been used productively.

Among the leading technology providers, it is worth mentioning the Canadian EvolutionQ, the US-based QuSecure, the Swiss IDQuantique, as well as the Italian QTI - Quantum Telecommunication Italy, recently acquired by Telsy, the TIM Group's centre of expertise for communications security and cybersecurity.

1.4 Quantum Sensing

Among quantum technologies, quantum sensing is responsible for the creation of **ultra-sensitive measurement sensors** designed to detect minimal variations in physical quantities such as time, gravity, magnetic field intensity, acceleration and temperature.

From a metrology point of view, this means, on the one hand, the possibility of obtaining much more accurate measurements of physical quantities that can already be detected using conventional sensors, but, on the other hand and above all, the possibility of measuring physical quantities that cannot otherwise be detected with the instrumentation currently available.
Therefore, this type of instrumentation allows critical problems to be addressed in contexts where measurement sensitivity is crucial, such as in the detection of very weak magnetic fields in the human brain or low-intensity gravitational fluctuations in geophysics.
The calculation of elapsed time can also benefit from quantum atomic clocks, whose greater accuracy enables the construction of new generations of GPS systems.
In a nutshell, quantum sensing represents a new generation of metrology technologies capable of pushing the limits of standard sensors, revolutionising the methods of remote observation, navigation and monitoring.

Industrial applications

Quantum sensing is already a near-production technology in numerous areas:

- **Healthcare**: devices for generating neurological scans, useful, for example, as a tool for preventive and non-invasive diagnostic investigation of diseases affecting the nervous system
- **Geology and environmental surveys**: quantum gravimeters to detect underground voids, aquifers or volcanic activity
- **Defence and security**: long-range unidentified object detection and automated navigation systems based on untraceable quantum radars/sonars
- **Precision manufacturing industry**: manufacture of sensors for nanomachines to make their action monitored and programmable
- **Aerospace and autonomous mobility**: tools for orientation and localisation in signal-free environments such as outer space

Major technology providers include the Australian Q-CTRL, the US-based SandboxAQ, and the Italian Quantum Ket, which specialises in the production of geophysical and biomagnetic quantum sensors.

1.5 The Year of Quantum

Awareness of the strategic importance of quantum technologies is also growing at institutional and supranational level.
2025 has been proclaimed the centenary year of quantum mechanics, prompted by the United Nations, which accepted the invitation of scientists from around the world to highlight this event.
The United Nations emphasises how all the technologies and theories born out of quantum physics contribute to both the economic and social development of humanity.

The International Year of Quantum Science and Technology initiative identifies six macro areas on which researchers, institutions and policymakers should focus their attention, efforts and investments:

- **Health and Wellbeing**: develop diagnostic imaging and support the creation of new medicines and vaccines
- **Reduced Inequalities**: make quantum solutions accessible to everyone thanks to an open science approach
- **Industry and Infrastructure**: develop new materials
- **Economic Growth**: ensure the security of the economic and financial infrastructure
- **Climate Action**: environmental monitoring and development of new climate models
- **Clean Energy**: design new low-cost solar cells and low-emission lighting systems

International Year of Quantum Science and Technology (IYQ)

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2025 Market and Ecosystems

Chapter 1 presented the fundamentals of quantum technologies and the main application families. This second chapter focuses on the evolution of the global quantum market, analysing its structure, key players and growth prospects.

In many respects, the quantum technology ecosystem represents a competitive battleground between countries and groups of countries for dominance over the technology and its entire value chain. The impact that quantum technology will have on many industrial, scientific and economic sectors will indeed be transformative and disruptive.

The international quantum market is experiencing a growing role for public and private investment.

Market data, including growth trends and competitive dynamics among the main ecosystems (divided into North America, Europe and Asia), suggest that multiple market and industrial challenges will need to be addressed over the next 5–10 years. Governments and public bodies around the world are promoting the emergence of industrial supply chains in the quantum sector by creating initiatives and technology parks, public-private partnerships and medium- to long-term development strategies.

The chapter closes with a reflection on the future prospects of quantum technologies, concentrating on the theme of technological sovereignty and global competitiveness.

2.1 Market

The quantum technology market is transitioning from the laboratory to industry, with sustained growth in public and private investment. According to the McKinsey *Quantum Technology Monitor - June 2025* report, the industry is still in the early stages of its life cycle. However, projections indicate significant economic potential, with applications ranging from health to finance, energy to mobility, and many other sectors. Based on the tangible technological potential, the quantum market is divided into three fundamental pillars: quantum computing, quantum communication and quantum sensing.

Technology	Value in 2025 in USD billion	Expected value in USD billion
Quantum computing	1.2 – 1.4	9.5 (2034)
Quantum communication	1.3 – 1.4	13.0 (2034)
Quantum sensing	0.3 – 0.4	1.2 (2032)

Sources: Future Market Insights, Precedence Research, Fortune Business Insights

The **quantum computing** segment is currently attracting most of the media attention and investment, despite remaining technologically immature in many of its architectures. However, it is also the sector with the greatest potential for value creation, even though most applications are only expected to be in prototype form.

According to analysts, quantum computing and quantum communication are currently the two segments with the highest market value, with roughly equivalent estimates of between $1.2 and $1.4 billion in 2025. However, quantum computing is the area attracting the most attention from investors and the media due to its potential for industrial transformation.
Average annual growth is between 23% and 31%. Applications focus on the simulation of chemical systems and materials, complex optimisation in industrial and financial contexts and integration with artificial intelligence. Furthermore, particular importance is given to the Quantum-as-a-Service (QaaS) model, which allows access to quantum resources via cloud platforms (see Chapter 4).

The **quantum communication** sector, focused on quantum cryptography and secure data transmission, is also expanding rapidly. The market is valued between $1.31 billion and $1.41 billion in 2025 and could exceed $13 billion by 2034, with annual growth exceeding 28%. This area is strategic for applications in defence, finance, public administration and telecommunications.

Quantum sensing, although less well known to the general public, already has practical industrial applications. With a current value of approximately $377 million and a forecast of $1.2 billion by 2032, it is used in sectors such as healthcare, defence, navigation in environments without GPS coverage and precision agriculture.

With more than $15 billion, China leads in public investment in quantum technologies

According to McKinsey, up to April 2025, a total of more than **$54 billion in public funds** have been invested in support of quantum technologies. China's leadership stands out ($15.3 billion), followed by the European Union with $8 billion, Japan with $7.4 billion, the USA with $6 billion and Canada with $2.5 billion. Alongside these, Australia, the UK and South Korea are also pursuing ambitious national programmes, while there are also significant state initiatives in the US, such as the $500 million in Illinois and a $1-billion plan in Maryland to support the development of quantum infrastructure.

Private investment is also growing rapidly: in 2024, there was approximately $2 billion in venture capital funding for quantum start-ups and scale-ups, up 50% from the previous year. This figure reflects renewed momentum in the sector following the slowdown after the peak in 2022, with investment volumes remaining around 6 times higher than 2019 levels. According to the McKinsey report, the global quantum technology market is estimated to reach a total value of $198 billion by 2040.

Quantum technology development is concentrated in three major geographical areas: North America, Europe and Asia. Each of these has initiated substantial public and private investments, supported the launch of start-ups and outlined national strategies to consolidate a competitive advantage in an emerging sector considered to have a high economic impact.

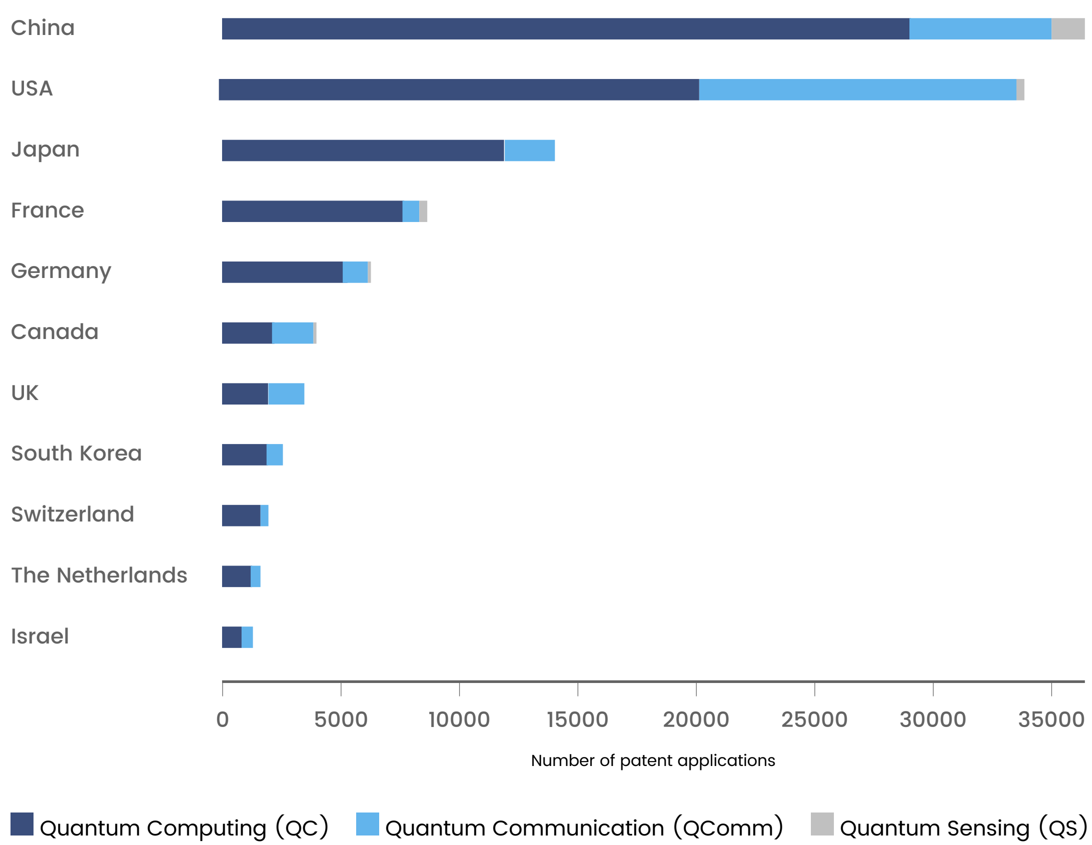
The United States has earmarked $6 billion in public funds for research and development of quantum technologies, most of which has been channelled through federal programmes, research organisations and government agencies.
The US market is marked by a high level of private investment. Between 2015 and 2023, over 50% of all global venture capital investment in quantum technologies was concentrated in the United States. The US has the largest number of active start-ups in the sector, with more than 100 companies operating in the field of quantum technology.
In the quantum computing sector in particular, the United States is the ecosystem with the highest market value: approximately $1.44 billion in 2025.

Canada has also earmarked $2.5 billion in cumulative public funds for the quantum sector. The country maintains a prominent role in academia and has a growing presence of start-ups, especially in quantum sensing and quantum communication. Between 2015 and 2023, Canada received about 5% of venture capital investments globally.

Shifting the focus to the European Union, investments exceeded more than $8 billion in public funds for quantum technologies, placing the EU in second place globally. This figure includes both centralised programmes (e.g. *Quantum Flagship*, funded

with over €1 billion) and national projects of individual Member States. The European EuroQCI programme, for example, aims to create a secure continental quantum communication network by 2027. The resources allocated at EU level and by individual Member States for this infrastructure exceed €500 million.
According to McKinsey, the level of private funding in Europe remains low compared to other global clusters. Between 2015 and 2023, the continent attracted about 16% of total global venture capital investment, about one-sixth of that of the United States. As of September 2025, Europe has over 100 start-ups operating in the quantum sector, with a strong concentration in countries such as Germany, France, the Netherlands, Finland, Italy and Spain. Germany is the strongest market in terms of size and industrial capacity, followed by France. However, there has also been growth in the Italian ecosystem, with an increasing number of initiatives related to quantum sensing, photonics and Horizon Europe programmes.

Patent applications in quantum technologies by country and area (2000-2024)
Source: LINKS Foundation analysis based on McKinsey data



In Asia, on the other hand, China is the country with the highest public investment in quantum technologies, with $15.3 billion in cumulative public funds, over 40% of global public funds. In addition to its financial leadership, China stands out in scientific production and intellectual property: it ranks first in the world in terms of the number of publications in quantum physics (approximately 42% of global publications in 2024) and patent applications in quantum computing (32% of the total), surpassing the United States.

In the private sector, the level of investment in Chinese start-ups is still lower than in the US, though growing strongly: in 2023, China accounted for about 10% of global private quantum investment.

Also in Asia, Japan has announced a $7.4-billion investment package for 2025 alone, aimed at developing quantum technologies and advanced semiconductors. This is one of the most globally significant public interventions, catapulting the nation to the top of the world rankings for state funding, just behind China and Europe, and ahead of the United States. These funds are part of a broader strategy promoted by the Government of Japan to strengthen technological sovereignty in strategic sectors such as quantum computing and artificial intelligence, integrate quantum technologies into advanced manufacturing, cryptography and transport, and finally encourage collaboration between large industrial groups and academic research centres, with players such as NTT, Toshiba and Hitachi already involved in pilot programmes and regional quantum networks.

Quantum technologies will be analysed in chapters 3 and 4 of the report, focusing on their transition from theoretical and experimental concepts to tools in an advanced implementation phase in industry or even already applied in practice. The three main technology families, quantum sensing, quantum communication and quantum computing, show different levels of technological maturity and adoption, but share the potential to profoundly transform strategic sectors, from energy to transport, healthcare and logistics.

Quantum sensing is the technology that has already reached the highest level of industrial maturity. Based on principles such as superposition of states, entanglement and interference, a quantum sensor can detect infinitesimal variations in physical quantities with a precision that is unattainable by classical sensors. Applications that are already in operation today include the use of magnetometers for non-invasive brain imaging, interferometers for inertial navigation without GPS, and gravimeters for detecting underground structures or natural resources. Quantum sensors are already used in the aerospace, defence and medical sectors, as well as in the monitoring of critical infrastructure.

Quantum communication, still in its consolidation phase, **is now being implemented in real applications, mainly thanks to the Quantum Key Distribution (QKD) protocol**, which enables the secure exchange of cryptographic keys by exploiting the properties of quantum mechanics. This technology guarantees physical, rather than just algorithmic, security of communication: any attempt at interception alters the quantum system itself, making the attack detectable. In operational terms, QKD has been tested on terrestrial fibre optic networks and also on satellite links. Concrete applications have already been implemented in the financial, telecommunications and defence sectors, while in Europe projects such as EuroQCI are working on the creation of a true continental quantum network.

While quantum computing represents the technology with the highest transformative potential, it is still in an advanced stage of development. Quantum computers exploit the properties of qubits – superposition, entanglement and interference – to perform calculations on an exponential scale compared to traditional computers. Quantum architectures currently in operation are already available via the cloud, and several start-ups and large companies (such as IBM, Google, Pasqal, and IonQ) are developing quantum hardware and software for industrial applications. In sectors such as pharmaceuticals, energy, transport and finance, pilot projects are already underway to optimise complex processes, simulate molecular structures or innovative materials and solve problems of routing or dynamic management of electrical and logistics networks.

A driver for the emergence of new technological and industrial hubs

Quantum technologies are not only revolutionising key industrial sectors, but are also contributing to the emergence of new technological and production clusters.

Quantum sensing has favoured the creation of industrial clusters in the biomedical, geophysical and defence sectors, thanks to the miniaturisation of sensors and their integration into advanced measurement and detection systems.

Quantum communication, through projects such as EuroQCI and QUID, is activating collaborative networks between telecommunications companies, data centre operators and research centres, consolidating Europe's strategic infrastructures.

Finally, quantum computing – partly thanks to its availability via the cloud – is generating application ecosystems around universities, technology providers and companies interested in developing use cases in logistics, energy, healthcare and finance. These emerging clusters are a key indicator of the ongoing transition from the promise of quantum technologies to their tangible economic impact.

2.2 Ecosystems

The transition from research to industrialisation of products and their entry into the market is complex and, in some ways, non-linear, particularly for potentially disruptive technologies such as quantum technologies. The creation and promotion of new industrial supply chains is one of the most interesting ways to facilitate the transfer of skills, and therefore of added value, from the academic world to the business world. In the case of quantum technologies, this approach becomes even more fundamental than in other deep tech fields due to the great complexity required to make them truly market-ready.

The **ecosystems dedicated to quantum technologies** that currently exist in some countries around the world bring together public and private research centres, universities, companies and start-ups, investment funds and major public players. The three quantum technologies are not currently represented equally: most of the attention is focused on computing and, to a much lesser extent, on communication, with sensing taking a back seat.

Specialised resources are key to the development of a quantum ecosystem

Focusing on quantum computing is of interest in order to understand how these ecosystems came about and how they are consolidating. Public and public-private investment is essential both for the physical construction of environments dedicated to research and experimentation, and for the ability to attract and retain the necessary **human resources**. Specialised researchers and technicians are an essential factor in the success of a quantum deep tech ecosystem. At this specific moment in history, their availability is limited, on the one hand, by the high degree of specialisation required and, on the other, by competition from other emerging technologies, particularly in the field of Artificial Intelligence.

2.2.1 European Union

The development of quantum technologies at European level takes place on several levels, with a multilateral and partly cooperative approach. **The European case is different from any other globally** due to certain characteristics specific to this geographical area. In fact, while other countries have national and regional projects, the supranational level proposed by the European Union and its agencies is added here.

Europe: difficulties in industrialising great technological expertise

Another feature of the European scenario is the high level of technical expertise in research centres and universities, where, quantum mechanics for example, the basis of the second quantum revolution, originated. However, this is not matched by the actual ability to implement discoveries in products and services to be brought to market. With a few exceptions, the old continent has so far been unable to ride the wave of technological revolutions of the last 25 years and create new companies capable of scaling up and establishing themselves in the global market. This is a widespread problem common to many areas of technology, where Europe lacks the equivalent of the so-called US Big Tech companies, which are very large technology companies capable of financing significant research and development activities over long periods of time and then bringing them to market.
Launched in 2018, with a time frame of 10 years and a budget of approximately €1 billion, the **Quantum Flagship** is the European Union's tangible response to the need to combine excellence in research with the scalability of results on the market.

The Quantum Flagship features four key areas in quantum technologies: quantum **computing**, quantum **simulation**, quantum **communication**, quantum **sensing and metrology**.
The main purpose of the initiative is to encourage the creation of new companies that have the ability to scale up and bring innovation to European and global markets. The Quantum Flagship is now fully operational.

Quantum Tecnologies Flagship

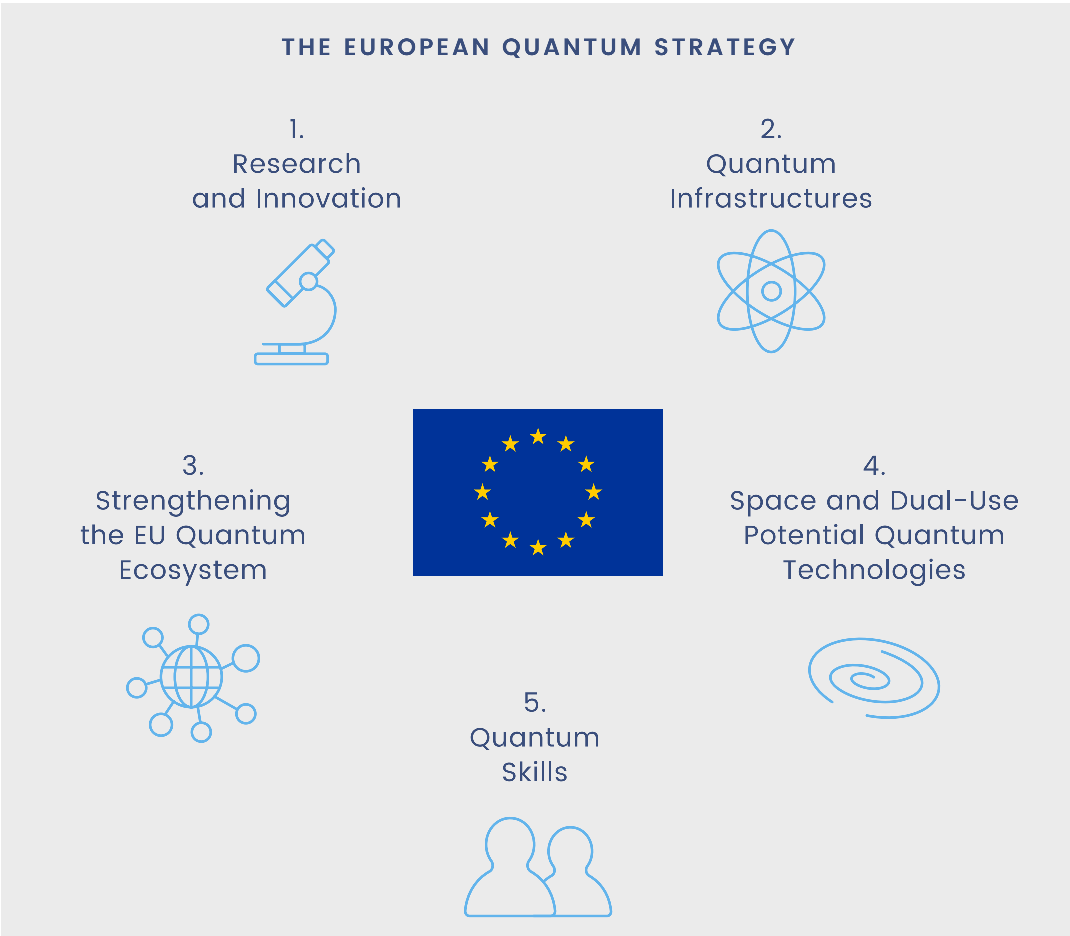
In July 2025, the European Commission published an official communication on the Union's quantum strategy. The *Quantum Europe Strategy: Quantum Europe in a Changing World* updates the EU's quantum technology strategy in agreement with the Member States in a profoundly different geopolitical context from the one that gave rise to the Quantum Flagship in 2018.
Political and financial instabilities at global level have highlighted the need for Europe to become increasingly independent and autonomous scientifically, industrially and economically in leading-edge sectors,

particularly in disruptive ones such as quantum tech. Since 2023, quantum technologies have been recognised by the EU as critical to the Union's development and security.
The new Quantum Strategy highlights major scientific achievements within the Union, which are unfortunately accompanied by a limited ability to bring innovations to market and significant fragmentation in funding and managing research and industrialisation programmes.

The Quantum Strategy of 2025 is based on five areas:

1. **Research and Innovation**: besides maintaining leadership in research, the EU wants to focus on the exploitation of this knowledge under the mottos *From lab to the fab* and *Apply and Use*

2. **Quantum Infrastructures**: the Union and its Member States jointly sponsor the creation of enabling infrastructures. Some examples fall under the initiatives EuroHPC JU, Quantum Communication Infrastructure - EuroQCI or the new satellite programme IRIS[2]. Enabling initiatives include those already launched for supercomputing, those dedicated to terrestrial, space and secure communications, and also new activities in the field of sensing, with a focus on quantum gravimeters and Quantum Magnetic Resonance Imaging (Q-MRI)



3. **Strengthening the EU Quantum Ecosystem**: in this case, the aim is to reduce fragmentation across the sector's value chain in Europe in order to promote the industrialisation and production of European quantum chips, including through dedicated initiatives such as the *Chips Joint Undertaking* (*Chips JU*). The first six pilot lines for quantum chip production will be announced between 2025 and 2026, with the first European quantum chip foundries expected to be operational around 2030. A new *Quantum Chips Industrialisation Roadmap* will be released by 2026. At the national level of individual Member States, the network of Quantum Competence Clusters (QCCs) is being expanded. In addition, investments are planned in start-ups and scale-ups, as well as in the creation of legislation to facilitate the implementation of quantum tech

4. **Space and Dual-Use Potential Quantum Technologies**: the focus is on integrating quantum technologies with dual-use potential into all European strategies in the fields of space, security and defence in order to strengthen both the strategic autonomy and competitiveness of the European Union

5. **Quantum Skills**: although Europe boasts an excellent academic base, there is a severe shortage of personnel with vertical and applied skills. In 2026, a *European Quantum Skills Academy* will be created, accompanied by a *Quantum Talent Portal*

Numerous initiatives are underway across Europe, increasingly carried out in coordination with the European Union and other Member States.

Germany can be considered the cradle of quantum mechanics thanks to its great scientists of the 20th century. The Federal Republic has now launched substantial funding measures for all quantum technologies, leveraging its extensive network of research centres and public-private partnerships, with the Max Planck and Fraunhofer centres at the forefront. One of the main German clusters is located in Munich: **Munich Quantum Valley** focuses its activities on quantum processor technologies and software platforms for quantum computing and complex simulations.

Munich Quantum Valley

In the Thuringia region, the focus of the local cluster is on photonics and quantum sensing. Other clusters are emerging in the more industrialised regions and in the university cities of Hamburg and Berlin. Germany can count on a solid industrial structure, including in the semiconductor sector, and on large companies that are investing in quantum technology, such as Bosch, Zeiss, Deutsche Telekom, Siemens and Infineon.

For years now, **France** has been pursuing a clear strategy to build a national ecosystem that is as comprehensive as possible and encompasses all quantum technologies. The first phase of **La Stratégie Nationale Quantique** saw an investment of around €1 billion over the period 2021-2025. Additional funds are planned for the national strategy for the growth of disruptive technologies, which includes quantum technology, by 2030. The French programme places significant emphasis on major public research centres, with a view to exploiting quantum technologies for dual-use applications. Like Germany, France can also count on major industrial groups interested in the development of quantum technologies, such as Thales, Orange, Airbus, EDF, and others.

La Stratégie Nationale Quantique

France has three main clusters. The Paris and Ile de France area is home to a large number of universities and public research centres, including the Centre national de la recherche scientifique (CNRS). Activities are focused on photonics and the development of quantum machines and chips. The presence of start-ups and scale-ups is growing, with two leading players on the European scene: Pasqal and Alice & Bob.
The Grenoble area, characterised by many laboratories, specialises in quantum communication and quantum circuits. On the other hand, Toulouse's Aerospace Valley specialises in quantum sensing, with a focus on gravimeters and atomic clocks, for applications useful to the aeronautics and aerospace sectors.

The **Netherlands** has a highly integrated and vibrant ecosystem focused on quantum computing and quantum communication. The national **Quantum Delta NL** initiative was launched in 2021 with a time frame extending to 2035. The country wants to capitalise on the large number of quantum start-ups and the quality of its research centres and universities, with TU DELFT at the forefront, to increase the number of companies involved in this field. The joint venture between Delft University of Technology and the Netherlands Organisation for Applied Scientific Research – TNO has created **QuTech**, one of Europe's leading research centres for quantum computing and technologies for the realisation of the quantum internet.

Quantum Delta NL

Within the European Union, other relevant clusters can be found in:

- **Spain -** The Iberian country has recently adopted the **Plan Complementario de Comunicaciones Cuánticas** to foster the implementation of quantum technology in communications. The dynamism of universities and research centres is promoting the creation of start-ups and participation in major European projects

- **Finland -** The country has carved out an interesting role for itself as a full-stack and end-to-end manufacturer of quantum computing technology, not least because of its strong electronics hardware design capabilities and numerous specialised research centres. **IQM**, presented in Chapter 3, is a manufacturer of quantum machines that is emerging on the world scene as one of the most interesting, both for computers designed for research and for quantum computers intended to work in synergy with classical High Performance Computing systems

- **Austria –** Austria plays a significant role in quantum research and applications, with a focus on communications, including in space due to collaborations with the European Space Agency, as well as quantum sensing. The **Institute for Quantum Optics and Quantum Information – Vienna (IQOQI-Vienna)** stands out among the public hubs firmly driving the field forward.

Other countries that are investing or planning new activities in the quantum tech sector are **Sweden**, **Luxembourg**, **Belgium** and **Poland**. Generally speaking, thanks in part to the impetus provided by the European Union, most of its Member States are developing or planning to develop activities related to quantum technology.

Within Europe, but outside the EU, Great Britain and Switzerland are significant players.

In particular, **Great Britain** is now a major global player in the study and implementation of all quantum technologies.
The country can leverage an excellent network of research centres, high-tech companies and well-qualified investors to manage high-potential but still immature technologies. For years now, the country has been implementing a clear strategy to promote the creation and growth of a national ecosystem that will enable it to become independent and, in the future, an exporter of quantum tech. In particular, the *National Quantum Technologies Programme* (*NQTP*) supports a very large number of start-ups, scale-ups and research projects in all the related fields, with a focus on quantum computing and quantum sensing.
The UK has a number of major companies involved in quantum implementation, including Rolls-Royce, Airbus, Toshiba Europe and BAE Systems, as well as a large number of world-leading universities and research centres. The hubs in Oxford, Birmingham, Glasgow and York collaborate with large companies and scale-ups.

National quantum strategy

Switzerland boasts a large network of universities and research centres, including international ones such as CERN, which enable it, despite its size, to be a true hub of quantum technology. The Geneva cluster can count on CERN and collaborations with the University of Geneva: this context gave rise to one of the first European companies to deal with quantum communication, **ID Quantique**. Other clusters are located in the Zurich and Lausanne areas, thanks to the large research centres at their technical universities and their dedicated laboratories, such as the Quantum Center at ETH Zurich.

#use case
The Italian ecosystem

Italy has embarked on a structured path to strengthen its position in the quantum technology sector. The Italian system is working to build a national quantum chain, capable of integrating scientific research, technological development and industrial applications.

Leading this transformation are two national initiatives: **the National Quantum Science and Technology Institute (NQSTI),** a national consortium set up in 2022 and consisting of 20 entities including universities and public research centres spread across Italy, and the **ICSC National Centre - High-Performance Computing, Big Data and Quantum Computing Research Centre**, which hosts a Spoke entirely dedicated to quantum and plays a central role in technology transfer and the management of hybrid classical-quantum computational infrastructures.

Spoke 10 – Quantum Computing

The NQSTI project represents one of Italy's largest investments in the field of quantum: it was financed by National Recovery and Resilience Plan (NRRP) funds with a total budget of €115.9 million. The aim is to cover the entire innovation chain, from strengthening basic research to applied experimentation, encouraging the creation of start-ups and spin-offs and contributing in particular to the growth of the sector in Southern Italy. This national infrastructure was created to turn Italy's scientific potential into tangible applications, supporting the development of quantum computers and secure quantum communication systems.

In this context, a number of strategic hubs are emerging that represent real laboratories of integration between applied research and industrialisation.
One of the main players in Italy's digital and quantum transformation is CINECA, the largest computing centre in Italy and one of the largest in Europe. Founded as an inter-university consortium, CINECA is not only a classic computing infrastructure. It is also taking on an increasingly active role in developing quantum computing, by testing various technologies. The organisation is collaborating with IQM (a Finnish company specialising in superconducting quantum computers) on the installation, expected between the end of 2025 and the beginning of 2026, of a 54-qubit quantum system, which will be directly integrated with the Leonardo supercomputer at its Bologna site.

The French company Pasqal will supply the EuroQCS-Italy quantum computer as part of the European High Performance Computing Joint Undertaking (EuroHPC JU). The 140-qubit analogue system is designed to be upgraded over the years and integrated into the Leonardo supercomputer: the machine should be fully operational by 2027. EuroQCS-Italy is co-financed by the Ministry of University and Research (MUR) and EuroHPC JU.

From a technological point of view, the challenge is not only scientific but also infrastructural. Leonardo is one of the most powerful supercomputers in Europe, already operational within the EuroHPC (the European Supercomputing Initiative). Integration with a real quantum computer is a key step towards **hybrid HPC-quantum models**, which will form the computational backbone of research and industry in the coming decades. Therefore, CINECA's role within the national strategy is twofold: on the one hand, it enhances Italian computing capabilities by integrating quantum technologies into existing systems, and on the other hand, it acts as a magnet for skills and industrial projects, facilitating the adoption of quantum computing by universities, companies and public administrations.

Cineca to House Italy's Most Powerful Quantum Computer IQM Radiance 54

The Naples area is particularly active thanks to the core research carried out by various departments of the Federico II University of Naples. At the "Ettore Pancini" Department of Physics, an initial prototype computer designed for research and testing of the technology, System Red, made by SeeQC (presented in Chapter 3), was assembled as early as 2023.

In 2024, the Naples University inaugurated Italy's first superconducting quantum computer, **Partenope**, which is open to the public for research activities, both public and private. Equipped with a 24-qubit processor, the system represents a milestone in ICSC's research and development activities. Partenope is accessible via the cloud and is a prime example of how scientific infrastructure can already be used by companies and researchers for real-world applications.

Inaugurato all'Università Federico II di Napoli il primo computer quantistico superconduttivo italiano

In May 2025, the first IQM quantum computer in Italy, a five-qubit system, was fired up at the Politecnico di Torino.

This project is the result of a collaboration between the Politecnico di Torino, the LINKS Foundation and the National Metrology Institute of Italy (INRiM), with the aim of providing research, industry and academia with an advanced platform for the development of quantum applications. This machine is the first commercial quantum computer in Italy and among the first in the world. What makes it unique is that, unlike many other installations that are still in the prototype phase or only accessible via the cloud, this system is operational and designed for commercial use by companies and research centres.
Its installation marks a fundamental step forward in the national strategy: for the first time, Italy has a local quantum infrastructure that can be used by businesses, public bodies and researchers, with immediate potential applications in sectors such as chemistry, logistics, finance and artificial intelligence.

LINKS, Politecnico di Torino e INRiM: acceso il primo computer quantistico IQM d'Italia

An important indicator of Italy's growing interest in quantum technologies is the number of registered patents. According to data from the Quantum Technology Monitor 2025, Italy has obtained **a total of 1528 patents** in the field of quantum technologies, 1443 of which in quantum computing, ranking tenth after the UK and South Korea.

2.2.2 United States

The United States has always been held up as an example for its ability to innovate and bring cutting-edge products and services to market.
Even in the case of quantum technologies, the US remains a very open and competitive ecosystem, where public investment in research is accompanied by substantial private funding that fosters entrepreneurial vibrancy of that productive fabric. The US approach is geared towards innovation and competitiveness. In this country, synergies between academia and industry are well established: the quantum sector has benefited from this approach. The United States is actually the only global player where all stakeholders in the quantum technology value chain are present: the public sector (including the military), *Big Tech* companies, start-ups, and public-private partnerships.

United States: a complete value chain

The **National Quantum Initiative (NQI)** is defined on the project's official website as "*a whole-of-government approach to ensuring the continued leadership of the United States in quantum information science and its technology applications*". Indeed, the US aims to maintain its technological leadership position across the entire value chain. The NQI was signed in 2018, with the aim of creating clusters across the US to facilitate the grounding of research, subsequent testing, tech transfer and standardisation activities.

The activities carried out by the United States Government are based on the guidelines outlined in the 2018 report, *A National Strategic Overview for Quantum Information Science*, which identifies six areas for action: science, workforce, industry, infrastructure, economic security, and international cooperation. The proposed strategy is holistic in that it is geared towards strengthening all components that may be affected by the quantum revolution.
These technologies are considered necessary from a scientific and industrial point of view, including for the broad field of national security in the broadest sense, with a very wide range of public and private stakeholders involved, including many agencies and ministries, and in particular the Department of Defense (DoD), the US Department of Homeland Security and the Defense Advanced Research Projects Agency (DARPA), i.e. the agency that manages the research and implementation of new frontier technologies, for military or dual-use applications.

The US is working hard to consolidate its quantum industrial base. The construction of testing infrastructure and collaborations between research groups and companies are seen as a way to promote knowledge transfer and accelerate research towards actual products. Furthermore, emphasis is placed on the importance of having a highly skilled workforce in this sector: training and the presence of researchers are outlined as enabling factors for achieving significant results in bringing quantum technologies to market.
Strategies suggested by the United States Government include identifying resources, especially manufacturing resources, that can be used or redesigned for the development and production of quantum technologies. Once again, the bulk of the focus is on computing.

National Quantum Initiative

The presence of Big Tech companies is proving to be a driving force for research in the US ecosystem and, ultimately, a major competitive advantage. IBM, Google, Amazon and Microsoft are investing billions of dollars in research, collaborations with academic institutions and universities, and the development of joint ventures with other companies and start-ups. These multinationals are acting as catalysts for the creation of quantum computers in particular, as discussed at length in Chapter 3 and in some in-depth analyses, such as that on the cloud applied to quantum computing in Chapter 4. The presence of *Big Tech* companies facilitates the creation and development of start-ups, which can become suppliers of components and/or software. Furthermore, in many cases, start-ups play a pioneering role, in terms of open innovation with the support of these large companies.

Companies specialising in quantum computing are now well funded and, in some cases, already listed on stock exchanges, such as IonQ and Rigetti. As presented in the following chapters, these are accompanied by many start-ups and innovative medium-sized companies, including in the fields of quantum communication and quantum sensing. The size of the United States, combined with the large number of *Big Tech* companies and start-ups, has led to the creation of multiple clusters where public-private partnerships are taking shape and innovation is fostered thanks to the synergy between universities, research centres and the private sector.

Among the main centres is the **Chicago Quantum Exchange (CQE)**, which brings together some of the most important research centres in the US such as the University of Chicago, the Argonne National Laboratory and the Fermi National Accelerator Laboratory. The Centre aims to promote all activities related to knowledge generation, testing and experimentation through advanced infrastructure and specialist training at all levels. The CQE is supported by the Illinois-Wisconsin-Indiana macro-region, where quantum technologies are seen as an opportunity for economic and social development in the near future, with significant employment and industrial benefits.

Chicago Quantum Exchange

Other clusters can be found throughout the country. Among the most active, particularly in terms of synergies between public, private, universities and research centres, are:

- City of **Santa Barbara, California** - California is a real driving force in the development of quantum computing in terms of hardware and software. Large universities, such as the University of California (UCLA), and *Big Tech* companies like Google and Microsoft are present
- **Boston Area in Massachusetts** - The Boston area is home to some of the country's most prestigious research centres and universities such as the Massachusetts Institute of Technology (MIT) and Harvard. Many start-ups dedicated to various branches of quantum technologies, particularly computing-oriented, are springing up in this area. In 2025, the giant NVIDIA announced an investment in this area to create a research centre dedicated to quantum computing and its integration with classical High Performance Computing architectures
- **College Park in Maryland** - The area is home to very active research centres, including that of the University of Maryland, and specialised companies, including IonQ, one of the US leaders in quantum computing. In early 2025, the public-private *Capital of Quantum Initiative* was launched to promote up to $1 billion in investment in the quantum sector, with a focus on quantum computing
- **Boulder Area in Colorado** - The Boulder area boasts a high concentration of universities and research centres. This cluster is characterised by a strong focus on research and implementation of all three quantum technologies. The U.S. Department of Commerce Economic Development Administration has created, with local partners, *Big Tech* and other companies, the TechHub called *Elevate Quantum*, one of the most active players in the United States in the field of quantum technology implementation and commercialisation

Finally, the US ecosystem is unique not only for being extremely effective in attracting human capital and foreign investment, but also and above all for promoting the creation and initial capitalisation of start-ups. There are a large number of **venture capital** funds, some of which focus on disruptive technologies, such as quantum, while others take a cross-industry approach. In both cases, the end result is the creation of an entrepreneurial environment in which start-ups can be created and eventually scale up very quickly, with extremely positive repercussions for the entire socio-economic system. From this point of view, the rest of the world, and Europe in particular, is following the US model on quantum.

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2.2.3 Canada

Canada has positioned itself as a major player in the development of quantum technologies thanks to an approach matured over the years and managed at the federal level. In 2023, **Innovation, Science and Economic Development Canada (ISED)**, presented the **National Quantum Strategy**, with a clear strategy to place Canada as a major global player in all quantum technologies: sensing, communication and computing. According to research commissioned by the National Research Council of Canada (NRC) in 2020, the quantum sector could be worth 139 billion Canadian dollars by 2045, creating around 200,000 jobs.

Canada's National Quantum Strategy

The so-called *Quantum Valley* in the Waterloo–Toronto area involves research institutions, universities, industries and specialised investors. In particular, the Institute for Quantum Computing at the University of Waterloo, the Perimeter Institute specialising in theoretical physics, and the Transformative Quantum Technologies Programme work in synergy to advance both basic research and the implementation of quantum technologies in market-ready products and processes. Some of Canada's most active quantum computing companies, such as D-Wave and Xanadu, were established in this context.

Canada also plays a significant role in the quantum communication sector, thanks in part to cooperation between public bodies, such as the Canadian Space Agency and private companies. The country is a world leader in quantum sensing, particularly in the fields of geology, biomedical, advanced monitoring and metrology. An example in Quebec, is **DistriQ - The Quantum Innovation Zone of Sherbrooke**, which has been building a true regional quantum ecosystem since 2022. The centre offers well-equipped spaces and easy access to funding and technological and industrial partners.

DistriQ

2.2.4 China

China is adopting a different strategy from its competitors.
The Chinese approach is long-term, planned and managed by the government: almost all activities are managed centrally. The Asian giant's goal in this sector is to build technological sovereignty first and foremost so as not to be dependent on external suppliers, with the medium- to long-term aim of becoming an exporter of quantum-based products and services. All quantum technologies are considered a strategic asset for national growth and security.

China: long-term planning to become the leader

The 14th Five-Year Plan, in force from 2021 to 2025, had planned investments, regulations and simplifications for the digital growth of China and its companies, focusing not only on classic supercomputing but also on quantum technologies. This orientation is part of a longer-term project that envisages China's independence in the production and management of frontier digital and IT technologies by 2035.

As presented in the first part of this chapter, China is the country investing the most in these technologies today and filing the most patents. One of the fundamental reasons for this Chinese peculiarity is the strong political will that is pushing China to become a leader in the quantum sector, both commercially and from a military and strategic point of view. In fact, the dual-use component of quantum technologies is considered strategic.

The strategic and interventionist vision of the Chinese model has materialised in recent years in a race to build state-of-the-art laboratories and scientific infrastructure in all major university cities. The Asian country can also count on a very large audience of large industrial groups and local *Big Tech* companies interested in using quantum technologies.

China's quantum ecosystems are concentrated in the large urban areas of **Shanghai, Beijing** and **Hefei**, where public research institutes and large companies are located.

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2.2.5
Japan, Korea, Australia

The Asia-Pacific region is a bloc characterised by growing trade and collaboration between its member countries. This approach is also reflected in the way key players are addressing the issue of quantum technologies, with the exception of China, which, due to its size and weight, has carved out a different and totally autonomous role for itself. Japan, Korea and Australia have made significant investments in quantum research and industrialisation. Japan and Australia both have strong relationships with European and US ecosystems that are working directly on the use of quantum technologies.

Japan has a strong academic tradition of studying quantum physics but, as in Europe, it has only recently accelerated its efforts to bring to market applications that exploit it. The first initiative in this regard – the *Quantum Technology Innovation Strategy* – was launched in 2020, reaching a significant turning point in 2025, when a new investment programme worth approximately $7.5 billion was announced to promote research and technology transfer. In addition to funding, the country aims to increase international collaborations in this area, with an acceleration planned from 2025 onwards.

Japan: the emerging player

Thanks to new funding and a clear new political orientation, Japan aims to achieve leadership in all aspects of quantum technology. At the heart of these efforts is strong collaboration between public research centres and major Japanese corporations such as NTT, Toshiba, Fujitsu and Hitachi.
To date, Japan's quantum ecosystem has been heavily concentrated in the vast urban area of Tokyo, where there are many laboratories belonging to large companies and university research centres, such as the University of Tokyo and the *RIKEN Center for Quantum Computing*.

South Korea's approach is pragmatic: the country wants to leverage its extensive experience and industrial strength in the electronics and semiconductor sectors and apply it to the quantum supply chain. Korea is determined to close the gap that separates it from its main competitors. In 2023, it presented a three-phase national strategy. In the first phase, 2023-2027, the focus will be on consolidation in quantum sensing, quantum communication and technical resource training. The second phase, 2028-2031, will focus on quantum computing and its industrialisation. The final phase, 2032-2035, aims to make Korea one of the most advanced countries in quantum technologies, including in all sectors related to dual-use and defence.
Korea is currently focusing on the hardware side of quantum technology, thanks in particular to large local companies in its industrial sector, such as Samsung and SK Telecom. Most of the activity is concentrated in public and private laboratories in the Seoul area. One of the main players is the **Korea Institute of Science and Technology (KIST)**.

Australia is another major player in the Pacific region. The country has a small domestic market and no large industrial groups involved in electronics or the production of dual-use technology equipment. However, Australia has a number of universities and research centres that are very interested in quantum technologies and have many active collaborations with the United States, Europe, Japan, South Korea and other technologically advanced countries.
The Australian Research Council's **Centre of Excellence for Quantum Computation and Communication Technology (CQC^{2}T)** in Sydney is a hub around which many of the country's quantum-related activities are taking shape, both in terms of research and business generation. Australia is focusing in particular on the quantum communication sector, where it has established collaborations with players from around the world. The **Quantum Technologies Future Science Platform** of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) is now proposing advanced research activities in sensing and communications in particular.

Australia's **National Quantum Strategy** was unveiled in 2023 with the goal of making the nation one of the leaders in quantum technologies globally by 2030 through targeted investments in infrastructure, research, human capital and private partnerships. The creation of the Australian ecosystem also includes a focus on issues related to the implementation of global standards and the ethical use of these technologies.

National Quantum Strategy

The Sydney area has a significant number of players involved in both research and the private sector, with many startups, including Quantum Brilliance, Silicon Quantum Computing and Q-CTRL. In addition, the synergy between the New South Wales government and the region's leading universities (Macquarie University, UNSW Sydney, the University of Sydney and University of Technology Sydney) has led to the launch of the Sydney Quantum Academy, a centre focused on vertical education in quantum technologies, technology transfer and the promotion of knowledge in this field.

Sidney Quantum Academy

2.2.6
Other Emerging Players: Israel and Singapore

Globally, many other countries are investing in quantum technologies or preparing national strategies to bring such activities to life. The cases of Singapore and Israel are interesting in terms of understanding how two small states can play a leading role, albeit with very different objectives and approaches.

Singapore created the National Quantum Office (NQO) in 2022, which is in charge of designing and implementing the national quantum strategy. A significant breakthrough was achieved in 2024 with the launch of *Singapore's National Quantum Strategy*, which envisages the establishment of infrastructure for research, technology testing and the training of quantum professionals and researchers. Singapore has a particular interest in quantum communications and their applications for telecommunications and information security.

Israel boasts world-class laboratories and research centres in the fields of physics and semiconductors. The country has set up a *National Quantum Initiative* to foster collaboration between public authorities, start-ups, large industrial groups and international players. The most active universities include the Israel Institute of Technology (Technion), the Weizmann Institute of Science and the University of Jerusalem. The country already has a long-standing group of start-ups working on various quantum topics, such as Classiq, and aims to exploit quantum technologies for dual-use applications.

2.3 Final Considerations

Over the next decade, the three quantum technologies analysed will reach a level of maturity and reliability that will enable them to make a significant impact on their respective markets. Quantum computing, in particular, is expected to achieve truly useful performance for practical applications from around 2030, as analysed in Chapter 3. However, there are still many complex challenges to be addressed from a scientific, standardisation and industrialisation perspective.

The analysis carried out so far seems to reveal fierce competition between geographical areas and industrial powers, with two important themes emerging. First of all, the quest for **technological sovereignty** across the entire quantum technology value chain: the US, China and the European Union have the size and resources to try to build ecosystems that are as autonomous as possible. However, this approach is also shared by smaller countries, albeit implemented on a more modest scale. Part of the motivation is geopolitical, as well as technological, since quantum technologies are often dual-use. The other very important issue concerns the ability to translate research and its results into **real products and services** for the market.

The creation of solid, well-organised industrial **supply chains** will be an essential prerequisite for exploiting the potential of quantum technology. Similarly, it will be important to plan effectively for the **training** of technicians and researchers working in this sector to ensure that research centres, start-ups and companies have the human capital they need to thrive. Many national strategies are strongly focused on this medium-term goal, partly to avoid the problems that many technology clusters and countries are experiencing today in 2025 in their search for specialised personnel, as is the case, for example, with artificial intelligence.

The market will play a key role in defining which ecosystems, industrial chains and technological approaches will be successful. From a timing perspective, quantum sensing and communication have an advantage in that they are at an advanced stage of industrialisation, with some products already available on the market. The biggest challenge will be quantum computing, which promises to revolutionise many markets but is still relatively far from reaching full production capacity.

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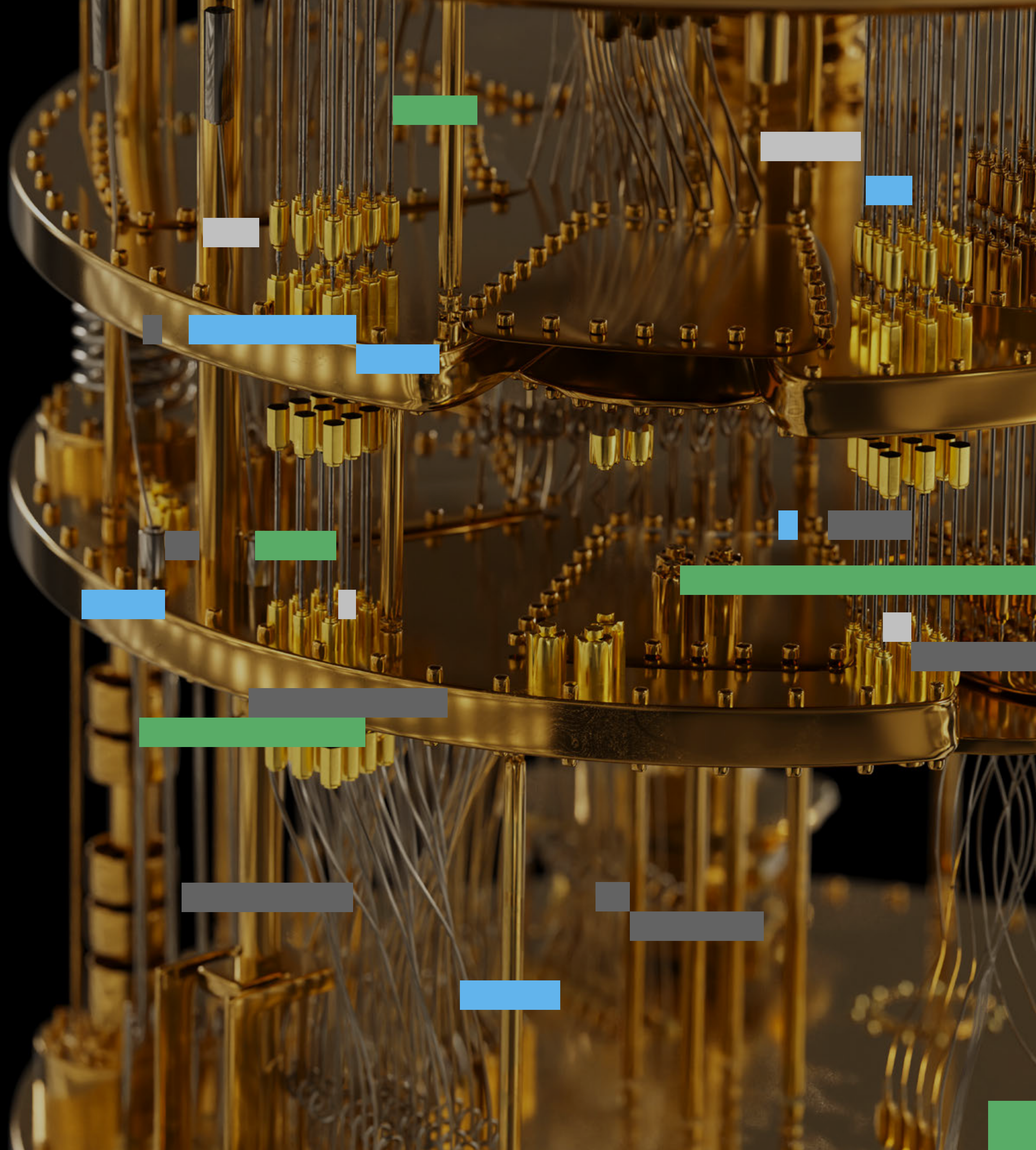
Technologies



As discussed in Chapter 2, in the sensor, communications and computing sectors, the market can be considered attractive in terms of turnover, geographical distribution and number of players involved.

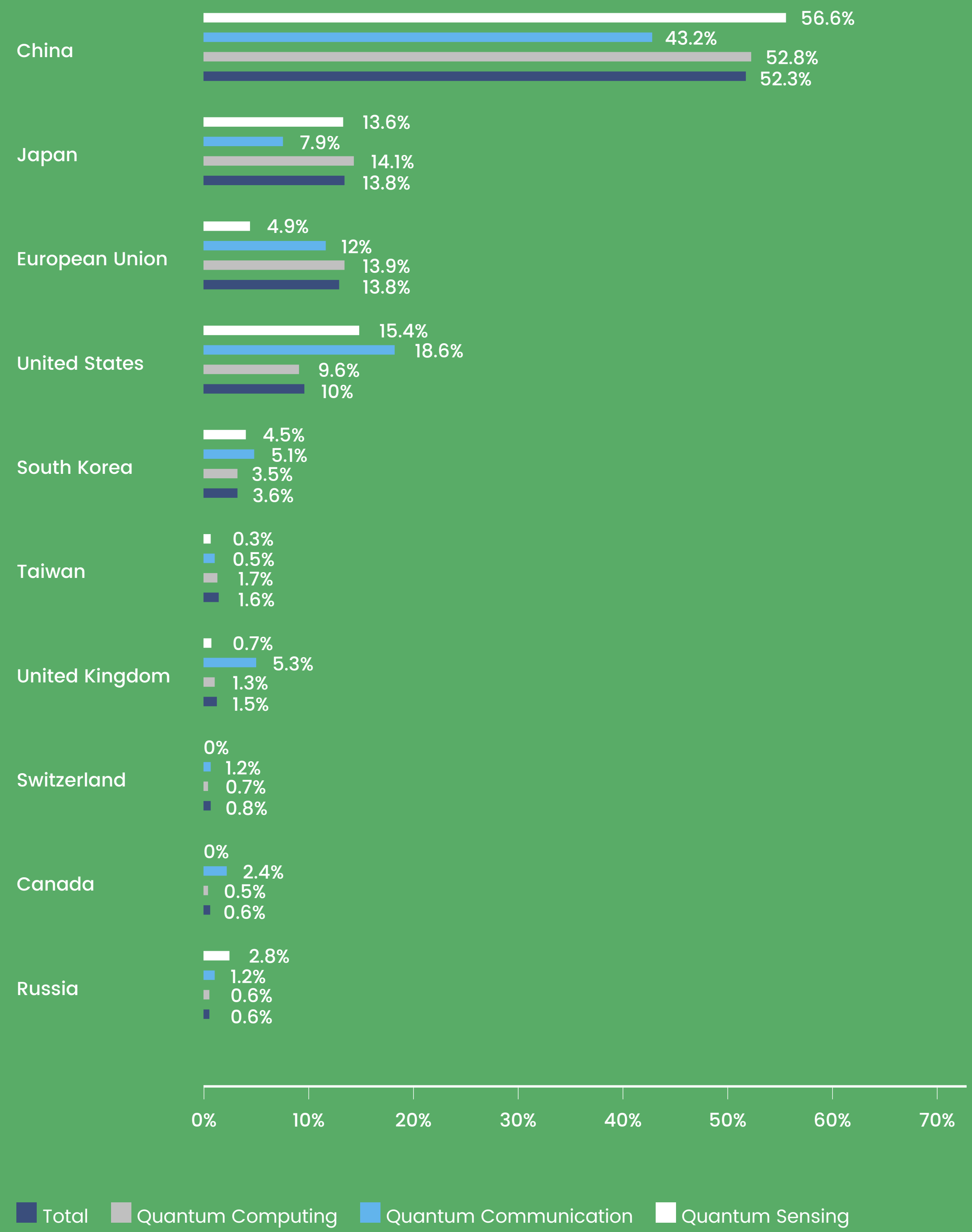
Quantum technologies are often associated with frontier technologies, far removed from practical applications. The reality is quite different, as many of them have gone beyond the confines of laboratories to enter industrial sectors.

In many respects, the three quantum macro-categories represent three killer applications that enable the sector to expand and reach the critical mass that fuels innovation.

From 2000 to 2022, the data available on patents granted in the three quantum sectors show how research and innovation in this field are concentrated among a few major global players: China, Japan, the European Union and the United States account for 89.9% of patents.

Quantum technology patent share from 2000 to 2022, by segment and country

Source: Statista



3.1 Quantum Sensing

The industrial sectors that are making the most use of these sensors are those that require highly accurate data analysis, potentially in special or extreme conditions. Adopting sensors that exploit the properties of quantum mechanics offers some significant practical advantages over traditional sensors: **higher precision, greater sensitivity and detection speed, miniaturisation**.

In general, quantum sensors provide high performance in the measurement of physical quantities, and in particular:

- **Time** and **frequency**
- **Gravity** and **variations of the gravitational field**
- **Magnetic fields**
- **Electric fields**
- **Accelerations** and **rotations**
- **Quantum optical properties of light**

Quantum sensors show great promise for a wide range of applications in the medical, chemical-pharmaceutical, energy, geodesy and geographical scanning sectors, as well as for environmental monitoring, navigation in the logistics and transport sectors, and space and defence-related activities. The industrial development of this branch of technology will revolutionise sectors that need ultra-precise data to enable new services.

QUANTUM SENSOR PROPERTIES

Greater sensitivity
Quantum sensors can detect extremely weak signals

Higher precision
They enable measurements with greater accuracy than conventional limits

Detection speed
They allow fast acquisition and real-time monitoring

Operational cost-effectiveness
They require lower costs and fewer resources than conventional sensors

Source: internal production

Measured size	Measuring tools	Areas of application	Main uses
Time and frequency	Atomic clocks	Navigation, telecommunications, finance	Ultra-precise synchronisation, timestamping
Gravity and variations of the gravitational field	Interferometers, atomic gravimeters	Geophysics, natural resources, volcanology, archaeology	Surveying underground structures, 3D maps without excavation
Magnetic fields	Magnetometers	Medicine, industry, defence	Brain imaging, non-destructive testing, advanced monitoring
Electric fields	Atomic sensors with various technologies	Diagnostics, advanced electronics	Local variation detection, component monitoring, maintenance
Accelerations and rotations	Gyroscopes, quantum accelerometers	Logistics, transport, space exploration	Autonomous navigation, GNSS backup, precision orientation
Light and photonic states	Optical interferometers	Metrology, secure communications, physical tests	Ultra-precise optical measurements, quantum imaging, optical sensing

Applications and challenges in the field of quantum sensors

The report "Bringing Quantum Sensors To Fruition" published in 2022 by the Executive Office of the President of the United States identifies five macro areas in which quantum technology has revolutionised, or will have a very strong impact on, the sensor industry in the near future:

1. Atomic clocks
2. Atomic interferometers
3. Optical magnetometers
4. Devices using quantum optical effects
5. Atomic electric field sensors

For the US Government, these applications are the forefront of what quantum sensor technology can offer to US industry today, which is heavily focused on high-value-added products and product-services. As a matter of fact, quantum sensors offer very interesting performance but are often characterised by higher costs compared to standard sensors.

Bringing Quantum Sensors To Fruition

A study carried out in 2024 by researchers from the McKinsey Center for Quantum Technologies, the University of Heidelberg and the University of Maryland on quantum sensor technology has highlighted how this technology already has real, market-ready applications, with significant growth potential and high impact for various industrial and scientific sectors.

The research focuses on four technologies for the creation of quantum sensors: solid-state spins, neutral atoms, superconducting circuits and trapped ions. Each of these technologies has pros and cons depending on the sensor desired. To date, the use of solid-state spins and neutral atoms has attracted considerable interest among manufacturers of quantum hardware for sensors, due to the flexibility and performance they can provide.
The study also highlights certain types of sensors that are considered very promising.

Superconducting Quantum Interference Devices (SQUID) exploit superconductivity to measure extremely weak magnetic fields through quantum interference in specific superconducting rings. These are highly accurate sensors that operate in cryogenic conditions, at temperatures close to absolute zero, and therefore require very complex thermal management, which is often bulky and energy-intensive. Today, they are used for applications such as measuring biological processes, including brain activity (magnetoencephalography), monitoring magnetic currents and fields, and geophysical analysis.

Atomic magnetometers are based on atoms in the gas phase, particularly rubidium or cesium, or on atomic defects in solids, such as nitrogen-vacancy (NV) centres in diamond, to detect magnetic fields. This type of sensor has the great advantage of often operating at room temperature while in many cases achieving a sensitivity similar to that of SQUID sensors. The ability to operate at room temperature allows for the creation of machines with portable sensors that consume much less energy than their SQUID equivalents due to the absence of cryogenic circuits.

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Quantum optical sensors use certain quantum states of light and photons. This category includes quantum interferometers and atomic clocks, used for ultra-precise time management in fields such as satellite navigation and metrology.

Quantum Sensing Can Already Make a Difference. But Where?

Significant growth is expected in the entire quantum sensor industry in the near future. Certain sectors are driving demand for ever-improving performance: healthcare, defence, energy, geodesy, navigation.

Healthcare is one of the most interesting sectors, where non-invasive monitoring of physiological parameters and parameters for early diagnosis of certain metabolic processes may provide an application capable of opening up huge new markets.
The geophysical sector, with its detailed mapping of gravitational variations to identify natural resources, underground structures and aquifers, also promises to attract considerable interest from research groups and companies. Furthermore, the current global instability linked to new forms of warfare is promoting the use of these sensors in security and defence for creating advanced, compact and energy-efficient radar systems, and in high-precision and/or inertial navigation.
However, these sensors are not yet fully developed, as there are still many challenges related to miniaturisation, standardisation and integration with existing sensors and infrastructure.

Atomic clocks

Atomic clocks have been on the market for some time. They represent a type of quantum sensor technology rooted in specific niches with defined markets and can be considered **the first** type of sensor to exploit quantum physics, revolutionising the way time is tracked thanks to the enormous precision they guarantee.

The first prototypes date back to the years between the late 1940s and 1950s.
Atomic clocks harness the resonance frequency that is characteristic of certain atoms, and thus the transition frequency between two energy levels of an atom, to measure the passage of time with extreme precision. The most common applications of atomic clocks are those where the highest possible accuracy in timekeeping is required.
The most common atomic clocks are based on the cesium-133 atom and the rubidium-87 atom. Cesium-133 is the international standard for defining the second: one second corresponds to 9,192,631,770 oscillations of the radiation emitted by the transition between two energy levels of the cesium-133 atom. On the other hand, Rubidium-87 is less precise than cesium but is often used in portable or less expensive devices.

Many countries have a **metrology** institute that uses atomic clocks for the national time scale, which then contributes to the global time scale. In Italy, the system that generates the Italian national time scale UTC(IT) is operated by the National Metrology Institute of Italy - INRiM, based in Turin. The INRiM is known globally for its advanced research activities and is the Italian contributor to the Bureau International des Poids et Mesures for International Atomic

Time. The research centre uses a cesium fountain atomic clock cooled to 89 kelvin (-184.15 degrees Celsius), which allows a sample accuracy of $2\ 10^{-16}$.

The Second

The **aerospace industry** extensively uses atomic clocks in satellite navigation satellites, where accuracy is a key requirement to accurate positioning for users on the ground.
The European Union's civil satellite navigation system, called Galileo and developed by the European Space Agency (ESA), has two types of atomic clocks on its satellites orbiting approximately 23,000 kilometres above the Earth's surface: rubidium and passive hydrogen masers.
The ESA claims that the rubidium clocks of the Galileo satellites are so accurate that they have a delay of three seconds over a million years of operation. For ESA and other operators of satellite navigation systems, this enormous precision is crucial to achieving ever better localisation for users on the ground: a deviation of a few nanoseconds from a distance of 23,000 km from the Earth's surface could in fact translate into a positioning deviation on the ground of metres or at most tens of metres.

How the Galileo atomic clocks work

ESA has signed a €12 million contract with a Leonardo-led consortium including the aforementioned INRiM to build new ultra-high-performance atomic clocks for the next-generation Galileo satellites.
The consortium will develop a new generation of pulsed optically pumped rubidium atomic clock. The new system will deliver an even more powerful signal that is smaller in size and consumes less energy than the systems currently used on Galileo satellites in orbit. The development of new ultra-high-performance atomic clocks will therefore be instrumental in achieving new standards of accuracy for Positioning, Navigation and Timing (PNT) services offered on the ground.

Contract for new Galileo atomic clock tech signed

Atomic clocks are also used in those areas where accuracy as to when a certain transaction took place is crucial, such as in the **financial** sector where stock trading are increasingly fast. For high-frequency traders, access to these assets can therefore represent a competitive advantage thanks to time stamps (digital labels that record the precise date and time when an event is recorded or data is generated) on transactions, which allow operations to be carried out with a very high margin of precision.

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Clocks that lose a hundredth of a second every million years

In 2025, a breakthrough was announced in the development of a new generation of even more powerful atomic clocks. The NIST-F4 cesium fountain atomic clock from the US National Institute of Standards and Technology (NIST) has a total systematic uncertainty of 2.2×10^{-16}, which translates into a loss of less than one second in 140 million years of measured time.
This new tool will enable applications that require the highest possible time accuracy to perform even better.

New Atomic Fountain Clock Joins Elite Group That Keeps the World on Time

The precision of atomic clocks is being increasingly demanded in sectors where time stamps play a fundamental role in the synchronisation of telecommunications networks, encryption systems, and economic and financial activities. However, these devices often require very complex infrastructure for their management, including from the point of view of cooling.

NIST, in collaboration with the University of Colorado Boulder, has set up a joint venture to test new atomic clocks such as those based on strontium atoms.
A researcher from that laboratory co-founded **Vector Atomic**. The start-up aims to bring quantum precision to all those critical sectors where absolute precision is required but where a standard atomic clock cannot be used and where a miniaturised one may not have the desired precision. Vector is designing a new generation of atomic clocks and atomic magnetometers offering high performance and compact dimensions, similar in size to a suitcase or a workstation to be inserted into a rack. Vector Atomic has already tested some of its solutions for inertial navigation on offshore vessels.

Vector Atomic

Aquark Technologies is a British start-up focused on miniaturising quantum technologies for sensing and computing. The company is working on products that make quantum technology as portable and usable as possible outside of laboratories, in real-world contexts. AQlock, their flagship product, embodies this approach: it is one of the first commercially available miniaturised, high-performance cold atom clocks. The company has developed a proprietary methodology for cooling atoms without external magnetic fields, reducing the complexity of the equipment. AQlock retains the advantages of a cold atom clock while offering a portable format. The clock is designed to operate in harsh or extreme environments.

Aquark Technologies

The atomic clocks introduced thus far are extremely high-performance but have two major limitations: they are often large and very expensive, making them difficult to mass-produce for widespread commercial use.

A miniaturisation process began in the early 2000s, leading to the launch of **Chip-Scale Atomic Clocks (CSACs)**, which fill a gap where larger, more complex systems cannot be used.

This technology has become commercially attractive in the last 5-10 years thanks to increasingly smaller sizes and new use cases.

In the transport sector, CSACs can overcome the lack of satellite navigation signal coverage to ensure high-performance inertial navigation. Drones and navigation equipment in critical contexts use this technology in both civil and military applications. CSACs can also be used as sources of backup time scales for financial applications or for sensors in remote areas or areas with poor access to orbiting satellites.

The US-based **Microchip Technology** is one of the largest manufacturers of miniaturised atomic clocks. Thanks to the experience gained over the years and feedback from its customers, the company is experimenting with the use of these devices in many different industrial and scientific fields. Microchip Technology specialises in the production of miniaturised rubidium atomic clocks characterised by low energy consumption, high reliability and resistance. The clocks are available in different versions, including rugged versions for military and space applications, such as on-board systems and payloads for small satellites in low Earth orbit.
Microchip Technology is also using its miniaturised clocks in extremely challenging environments, such as the submarine sector, where access to Position, Navigation and Timing (PNT) systems is necessary despite the inability to receive satellite navigation signals from orbiting systems. This new generation of atomic clocks is designed to ensure consistent performance over time despite the temperature and pressure fluctuations that can occur at sea. Their use will enable much more reliable sensor clusters for activities that rely on ultra-precise timing for monitoring and researching the ocean floor. The same technology could also be used for inertial navigation of drones and underwater robots (a topic covered by X-Plore – Ocean in this series).

Microchip Technology

Adamant Quanta has designed a new generation of miniaturised atomic clocks using artificially manufactured diamond crystals. These diamonds incorporate defects characterised by very specific quantum properties that are harnessed for the operation of the devices. The miniaturised atomic clocks in the QDi.AC series are extremely compact and robust. They are designed to be integrated into printed circuit boards as standardised electronic components, making them compatible with existing architectures.
Synthetic diamond technology as an atomic support can be advantageous in some specific cases where it allows for superior performance compared to already available CSACs, particularly with regard to clock stability and energy efficiency. QDi.ACs are used in application areas where business continuity is needed under extreme conditions, such as the defence and communications sector.

Adamant Quanta

Atomic interferometers

Another type of quantum sensor is that of **atomic interferometers**, designed to exploit the wave-like behaviour of matter highlighted by quantum physics.

These sensors are often based on ultra-cold atoms placed in a state of quantum superposition or may use light (optical interferometers).
The most significant advantage over conventional sensors is that continuous calibration is not necessary, as they are stable over time and can operate without drift even in difficult environments and for long periods of time.
At a scientific and industrial level, this type of sensor plays an interesting role in inertial navigation applications, where they can take the form of accelerometers and quantum gyroscopes, in geophysical research and in infrastructure monitoring. Both families of sensors are playing an increasingly important role in the transport and logistics sector. In some cases, they can be used in combination with each other, depending on the application requirements.

Among atomic interferometers, **quantum gravimeters** stand out due to their potential in industry and science.
This type of sensor is opening up new possibilities for detecting underground objects, aquifers or deposits of specific materials without the need for costly and time-consuming excavation. Some products are already available on an industrial and scientific level.
In 2022, for the first time, they were used to characterise the subsoil of volcanic areas: the Italian National Institute of Geophysics and Volcanology (INGV) used a quantum gravimeter to analyse magma movements in an area of Mount Etna. The experiment

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demonstrated the advantages of this technology in terms of the significant data collected on a continuous basis.

Creating detailed maps of the subsoil

In the future, the use of this technology could provide much more usable data than those currently available to understand the evolution of volcanic systems and areas subject to volcanic phenomena.
In this particular sector, some start-ups are investing in the development of products characterised by high reliability and compact size, the two most important features for a sensor of this type. Quantum gravimeters promise to revolutionise the exploration of underground resources, both on land and at sea, in terms of timing and cost.

In the near future, it will be possible to use these instruments to map the subsoil continuously, rather than just on a sample basis as is the case today, identifying deposits of hydrocarbons or other raw materials that have not yet been mapped or have only been partially mapped.

Atomionics from Singapore is engineering a new generation of gravimeters that exploit the properties of laser-cooled rubidium atoms to investigate the structure of the subsoil.
Their flagship product, called Gravio, is a very compact atomic interferometer designed to facilitate underground exploration on moving vehicles such as vans, helicopters or ships. The advantage of mobile use has the potential to be revolutionary compared to the gravimeters currently available, as it enables underground mapping with much greater precision, highlighting more quickly certain details that cannot be detected with current systems. This increased precision also translates into reduced costs: a survey over large areas can be carried out in less time and with greater accuracy.
The device is designed to detect gravitational variations that may lead to mineral or hydrocarbon deposits, underground infrastructure such as pipes or sewers, and areas characterised by the presence of water. Gravio is an evolving product with even more compact versions available in the future, which can be installed on drones or other types of vehicles for rapid surveys.

#video
How does Gravio, a quantum gravimeter, work?

M Squared was the first to introduce a commercially-engineered industrial quantum gravimeter to the UK market. The company has developed proprietary technologies for the manufacture of products using quantum technologies also in the fields of atomic clocks, quantum computers and advanced inertial navigation. The industrial quantum gravimeter from M Squared uses laser cooling to manipulate rubidium-87 atoms. The gravimeter accurately measures the area under examination, detecting objects, underground structures and geological formations without excavation. The system is equipped with software designed to facilitate the reading of results. The company focuses on applications related to geodesy, underground monitoring for the detection of deposits and archaeology.

M Squared

Quantum magnetometers

In the growing family of quantum sensing, new sensors are emerging that use various quantum mechanical principles to measure extremely weak magnetic fields: these sensors are the **quantum magnetometers**.

The exploitation of the quantum states of atoms as a source of data collection allows for spatial precision and resolution that classic magnetometers cannot achieve due to physical limitations. This new generation of magnetometers is beginning to be used mainly in industry for monitoring and maintenance activities in the infrastructure, machinery and biomedical applications sectors.

The health and medical sector is another area where research is progressing rapidly, with these sensors promising to open up new possibilities for ultra-precise, non-invasive diagnostics.
In particular, **Superconducting Quantum Interference Device (SQUID) magnetometers** have become the standard for magnetoencephalography (MEG), as they enable the detection of extremely weak magnetic fields produced by brain cell activity, which cannot be detected at this level of detail with standard sensors. However, SQUIDs require complex machinery to maintain the cryogenic temperature of the sensors, which increases their energy consumption.

Molecular imaging and precision diagnostics

This technology is rapidly evolving thanks to **Optically Pumped Magnetometers (OPM)**. OPMs exploit the quantum properties of atomic vapours at room temperature: system consumption and complexity are drastically reduced, as no cryostatic apparatus is required, and the reduced size allows for the design of wearable sensor helmets that are relatively light and comfortable to wear, enabling a certain degree of freedom of movement and paving the way for new forms of monitoring, including in the paediatric sector.

Other new-generation atomic magnetometers exploit defects in diamond crystals with **Nitrogen Vacancy (NV) technology**, and can even measure magnetic fields at the nanoscale. Their precision is so high that they have enabled laboratories to detect the activity of individual neurons.

Together, these technologies, combined with the growing availability of High Performance Computing resources capable of processing large amounts of data in a short time, will open up new prospects for molecular imaging and precision and personalised diagnostics.

Cerca Magnetics was founded as a spin-off from the University of Nottingham in the United Kingdom. The start-up has developed a proprietary magnetoencephalography system designed to be easily wearable for long periods of time, even by paediatric subjects, thanks to the use of OPMs. These new magnetometers are more compact than those of the previous generation, while still ensuring high-precision measurement of brain magnetic fields. Furthermore, the system does not require cryogenic cooling, allowing for a drastic reduction in energy consumption compared to traditional MEGs that require cooling. Cerca Magnetics is focusing its attention on brain imaging, with the medium-term goal of identifying new methods for the early diagnosis of debilitating neurological conditions.

Cerca Magnetics

The German company **Q.ANT** specialises in next-generation quantum photonic sensors based on nitrogen vacancy technology. The company's leading product is called Q.M 10, a very compact quantum magnetometer with a power consumption of 10W and a weight of 600g. It offers extremely high detection accuracy: the instrument is designed to be able to measure ultra-weak magnetic fields, with a sensitivity of up to 10 picoteslas operating at room temperature. These characteristics allow for potential use in many professional contexts, from medical diagnostics to industrial applications for ultra-precise monitoring of machinery and detection of quality or defects in certain types of materials.

Q.ANT

KWAN-TEK designs and manufactures magnetometers based on nitrogen vacancy technology. The company specialises in advanced quantum metrology and non-destructive testing of materials in industrial settings. The High Field NV Magnetometer is designed to be ultra-stable and therefore to effectively monitor real-time magnetic field fluctuations in equipment that produces very strong magnetic fields, such as certain physics experiments, particle accelerators, or magnetic resonance imaging machines. The use of NV diamonds makes the instrument stable over time, without the need for periodic calibrations, thus reducing costs and increasing its operational availability.

KWAN-TEK

Magnetic Resonance Imaging (MRI) itself exploits the principles behind quantum mechanics to collect data that are then processed to obtain increasingly detailed non-invasive diagnostic images.
Scientific research in this field is particularly interesting in terms of the possibilities that new MRI systems could offer in the future.

One example comes from the German company **NVISION**, which is working on a new technology that exploits recent discoveries in quantum physics to produce magnetic resonance images with a much higher resolution than those currently available, without the need to replace the machines currently in use. The company intends to increase the ability of today's MRI machines to detect certain types of cancer thanks to a form of pyruvic acid modified to make the nuclear spin of its carbon atoms more "visible" to the machine. As a result of this innovative approach, it will soon be possible to obtain much more accurate scans of the progress of tumours and metastases, as well as how they respond to therapies shortly after their administration.

NVISION

A highly innovation-oriented approach in the corporate world is being pursued by the German multinational **Bosch**, which has created an internal business unit that acts as a real start-up dedicated to quantum sensing, **Bosch Quantum Sensing**. The company's medium-term goal is to develop a new generation of high-precision, compact and energy-efficient quantum sensors. Therefore, Bosch is focusing heavily on miniaturisation, while ensuring impressive performance: in some sectors, the company aims to achieve measurements that are "*almost 1,000 times more accurate than those made by today's MEMS (micro-electro-mechanical system) sensors*".

Bosch Quantum Sensing

In Italy, the University of Bari spin-off **QSENSATO** is developing new-generation atomic sensors capable of performing ultra-precise measurements by detecting minimal variations in electric and magnetic fields. At the heart of the technology is the integration of atomic-photonic chips into miniaturised devices, which are used in strategic areas such as medical diagnostics, geophysics, GPS-free navigation and critical infrastructure monitoring.
Founded by a team of researchers, in 2025 it closed a €500,000 pre-seed round thanks to the entry of LIFTT and Quantum Italia, two Italian funds specialising in deep tech and quantum technologies. This investment will support the development of new prototypes, entry into the European and US markets, and the growth of the team.

Qsensato

3.2 Quantum Communication

Quantum mechanics is also revolutionising the telecommunications sector. *Quantum communications* employ the principles of quantum physics to make systems more powerful or to propose solutions and functionalities that cannot be achieved with systems based on classical physics. Superposition and entanglement between particles thus become enabling tools for safer and faster communication networks.

In the context of quantum physics, one of the founding assumptions is that measuring or observing any quantum system somehow disturbs its state. The result is that anyone attempting to observe or manipulate a form of quantum communication will leave some form of detectable trace.
The level of security is theoretically much higher than that achievable with non-quantum techniques. From this point of view, the use of quantum technologies for communications introduces the possibility of having systems characterised by **intrinsic security** since any intrusion or observation of data becomes physically detectable.

Similarly, studies and practical applications are emerging that aim to exploit entanglement to generate correlations between particles located at very significant distances. Under ideal laboratory conditions, it is possible to achieve distances of hundreds of kilometres on fibre optic networks and thousands in *Free Space* conditions, such as in the vacuum between satellites in Earth orbit or between satellites and ground networks. In real-life conditions, distances are shorter: research is focusing on this issue both to improve existing networks based on quantum technology and to find ways to better manage the quantum signal with quantum repeaters, whose development is still mostly theoretical and experimental. These correlations have the advantage of occurring instantaneously, without undergoing any kind of change due to distance, other interference or intentional tampering, ensuring **extremely fast and secure communication** of data or data packets.

Quantum Key Distribution and communications security

In the vast field of quantum communications, the **Quantum Key Distribution (QKD)** protocol stands out in terms of importance, research activity and practical applications. Compared to sensor technology, the entire quantum communications sector is at a lower level of industrial and commercial development. However, within this context, QKD is the protocol closest to mass diffusion, with many companies working on market-ready applications, if not already marketed (therefore with a high Technology Readiness Level).

As emphasised in the first chapter, the QKD protocol is not used to transmit messages or information directly: instead, QKD provides a set of inviolable encryption keys that can be used to exchange data over classical channels. **Therefore, QKD is a system for the secure distribution of cryptographic keys and not an encryption system.**

This feature makes it very interesting for upgrading existing communication infrastructures, with a focus on fibre optic ones. The implications of using this technology are significant from many points of view, including economic, strategic and social. The implementation of QKD can make a key contribution to the security and inviolability of the transmission of all sensitive information that underpins advanced societies and economies, in particular financial and banking data, personal data such as health data, data derived from business applications or activities, and finally military and strategic information, which may also include data used in activities relating to the protection of citizens, civil protection and emergency management.

QKD and the technology behind it are still being studied and tested, as some properties related to their development need technological refinements in order to be used on a large scale. One of the aspects currently being studied concerns the attenuation of quantum signals over long distances in certain types of networks. The technical complexity also affects both the equipment and the related production and management costs. Furthermore, QKD needs to be effectively integrated into communications transmission systems and data encryption algorithms. As with other similar technologies in the past, many companies and start-ups are working on engineering simpler, cheaper and more versatile QKD systems.

The main providers of Quantum Key Distribution technology are concentrated in Europe and North America. Research and development activities, as well as the creation of start-ups, are progressing very quickly at a global level, with China playing a very important role (see Chapter 2 for further details). In this particular case, it is important to emphasise that this technology is considered dual-use, as it can be used in both civil and military and strategic contexts. This versatility of QKD has generated a great deal of interest since the post-COVID-19 period, as communications security has taken on an extremely important role due to growing international tensions and increasingly impactful cybercriminal activities.

Another point of interest mentioned by many companies stems from the need to create systems for the transmission, management and storage of data that are already secure, since data stolen today could be decrypted in the future. Many analysts estimate that the technological replacement will take place around 2030, when quantum computers will be a reality that can be used to breach today's existing data protection systems.

#use case
Focus on Europe

The European initiatives aimed at creating a highly secure communication network both on the ground and in space, and at promoting collaboration between Member States for the protection of sensitive data through the use of quantum physics, include the **European Quantum Communication Infrastructure (EuroQCI)** and the **Open European Quantum Key Distribution (OpenQKD)**.

European Quantum Communication Infrastructure – EuroQCI

Open QKD

EuroQCI is an initiative whereby the European Commission has been collaborating since 2019, with the 27 Member States and the European Space Agency (ESA), on the design and deployment of a fibre-optic quantum communication network connecting strategic sites at national and cross-border level, including a satellite-based space component integrated into the new IRIS^2 secure space communication system (Infrastructure for Resilience, Interconnectivity and Security by Satellite).
The ground-level system makes use of existing infrastructure to create a secure nationwide communication network. In this respect, the design and architecture definition studies for EuroQCI are being carried out by two industrial consortia established by the European Union. The European Space Agency (ESA) is also expected to be involved with a view to integrating quantum technologies into the Union's space assets.

The **Open European Quantum Key Distribution** is an EU-funded initiative involving and bringing together multidisciplinary teams from several Member States, including Austria, the Czech Republic, France, Germany, Greece, Italy, the Netherlands, Poland, Spain, Switzerland and the UK. OpenQKD aims to promote the adoption of quantum cryptography, acting as a facilitator and multiplier for advanced technological solutions. Through cooperation between universities, industry and European start-ups, open test sites are being set up across Europe, accessible to external parties for field trials. This collaboration will significantly raise awareness and facilitate involvement with the QKD.

The **Quantum Italy Deployment (QUID)** is the Italian implementation of the EuroQCI, coordinated by the National Metrology Institute of Italy in Turin. This project aims to develop nodes in metropolitan quantum communication networks (QMANs), interconnected through the Italian Quantum Backbone, the infrastructure based on commercial fibre optics that covers the Italian territory by distributing time and frequency sample signals. Among the various objectives is also the merging of important sites for the connection between fibre-optic communication and the space segment of the European QCI to develop innovative techniques related to QKD, to increase the transmission frequency.

QUID: The implementation of quantum communication network in Italy begins

Founded in 2001, the Swiss company **ID Quantique** has been regarded as a pioneer and one of the world leaders in the marketing of QKD-based products and quantum security technologies for the past 20 years. The company was acquired by US quantum technology manufacturer IonQ at the beginning of 2025, although it currently retains its operational autonomy.
Over time, ID Quantique has stood out for its products that implement protocols for Quantum Key Distribution, and for those that exploit **Quantum Random Number Generators (QRNGs)** and **Single-Photon Detectors (SPD).** QRNGs exploit the probabilistic mechanisms of quantum mechanics to generate purely random sets of numbers, both for QKD protocols and for other applications related to security, tokenisation and simulation for advanced statistical models. This system is inherently non-reconstructible, unlike the Pseudo Random Number Generators (PRNGs) used in many applications today. SPDs are also used for QKD applications and for all those tasks related to ultra-precise optics, from quantum optics to spectroscopy.

ID Quantique's products have been integrated in telecommunication networks and by cloud providers, in systems used by commercial and public banks, and in central government communication systems. The company has developed quantum-based products, e.g. for the secure transmission of sensitive data (interbank, health, government data) or for certified digital signatures. ID Quantique has developed an extremely compact and energy-efficient QRNG chip for information security applications that can be used in a wide variety of application contexts: the *Quantis QRNG Chip*.
ID Quantique is an active participant in the European EuroQCI and OpenQKD projects, and has played a major role in QKD standardisation, an activity undertaken within ETSI and ITU.

ID Quantique

evolutionQ, founded in 2015 in Canada and with an R&D office in Germany, works on the topic of QKD from the point of view of software implementation for its integration into existing telecommunications networks. evolutionQ therefore does not produce QKD hardware but has focused on everything that enables the effective use of that protocol, using proprietary software technologies to create integration platforms for monitoring quantum security protocols in broadband networks, cloud networks and all types of networks that require very high security.

The *BasejumpQDN - Quantum Delivery Network* by evolutionQ is a platform designed to control and manage the entire chain of cryptographic key creation and distribution. The platform enables multi-vendor and multi-technology integration of technologies and products to adapt to evolving technology and needs. evolutionQ carries out projects and activities to assess the degree of exposure to quantum threats of an entity or company, called the **Quantum Risk Assessment**. This assessment allows us to understand and evaluate in advance the resilience of IT infrastructures and procedures put in place to counter complex attacks, particularly those that could be carried out by quantum computers. evolutionQ has carried out projects with major European telecommunications and transport companies and participates in OpenQKD.

evolution

QuSecure is a US company that has been active since 2019 in the development and design of advanced software solutions for communications security with a focus on the implementation of **Post-Quantum Cryptography (PQC)**. The company's software implements post-quantum QKD encryption in potentially all existing digital networks as the software platform is designed to be completely agnostic to the hardware used. This approach allows operators to be flexible in their choice of hardware and enables QuSecure to provide platforms that are considered future-proof, capable of adapting to new machinery. The company also develops hybrid solutions where PQC and encryption key management with QKD co-exist dynamically.
Frost & Sullivan named QuSecure *2024 Product Leader in The Global Post Quantum Cryptography Industry* due to its approach to multilevel security. The QuProtect™ platform uses post-quantum algorithms and Quantum Key Distribution to which a *cryptographic orchestration* layer is added to efficiently manage the transition from classical to quantum-safe algorithms in hot-swapping mode, without operational disruption. The level of security achieved is particularly high and flexible in managing threats, making it suitable for protecting critical infrastructure.

QuSecure

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KEEQuant was founded in Munich, Germany in 2020. The company stands out as a reliable partner for QKD applications thanks to its technology and the financing methods it has adopted to date. Data updated in the first half of 2025 show that KEEQuant has received funding exclusively from the European Union, without any other external funders: the company is therefore a prime example of a deep tech start-up in a sector where European technological sovereignty is strategically important.
KEEQuant develops systems by using standard coherent telecommunication technology with integrated photonic devices, designed to be easily scalable. The focus is on two product families, one for QKD for the generation of cryptographic keys for fibre optic networks and the second for cryptographic key management systems for telecommunications operators.

KEEQuant

LuxQuanta was founded in 2021 as a spin-off of the Institute of Photonic Sciences in Barcelona, Spain. The researchers focused on the main challenges related to the implementation of quantum technologies in European telecommunications networks. For this reason, LuxQuanta focused on the study and design of systems for Quantum Key Distribution that exploit a particular technology called **Continuous Variable Quantum Key Distribution (CV-QKD)**. This choice was made to ensure that LuxQuanta products can be easily integrated into fibre optic networks in Europe, guaranteeing plug-and-play installation directly into existing backbones, with scalability and good tolerance to signal loss and noise.
NOVA LQ®, the company's flagship product, exploits these characteristics to enable easy installation in racks where fibre optic network management equipment is located, ensuring coverage of distances up to 40 km. LuxQuanta already has several partnerships with European telco companies aimed at operational testing in real-world contexts of QKD services for the management of sensitive data transmission, including on cloud platforms.

LuxQuanta

QEYnet intends to combine the potential of QKD with that of the New Space Economy. Recognising that current prevailing encryption systems could become ineffective within a decade, the Canadian company is proposing a radical technological solution that involves the creation of a constellation of satellites to distribute globally available QKD technology keys.
To achieve this ambitious goal, QEYnet is specialising in the design and manufacture of miniaturised, energy-efficient quantum terminals for QKD. The company is studying and evaluating various options for managing the systems in orbit. Their hardware can be mounted as payload on commercial satellites or other types of specific vehicles, including ride-share. In the future, this solution will enable the creation of a scalable satellite network that could potentially compensate for the lack of terrestrial infrastructure in all those areas where it is not possible or economically viable to build it. QEYnet is collaborating with Canadian institutions and research centres, such as the National Research Council (NRC) of Canada or the Canadian Space Agency, to test its hardware and initiate pilot projects.

QEYnet

Protecting tomorrow's threats today

Australia's **QuintessenceLabs** is recognised as one of the most interesting players in data and transmission network protection in the Asia-Pacific region. The company is working to raise awareness among private entities and institutions about the importance of protecting data right now, both to prevent future attacks from quantum computers and to avoid scenarios in which currently encrypted data are stolen today to be decrypted in the future (the so-called harvest-now, decrypt-later scenario). This malicious scenario could in fact lead to enormous damage and loss of sensitive data, even years after the data were actually stolen.
QuintessenceLabs proposes different types of Quantum Random Numbers Generators with a full entropy approach and thus characterised by truly random number generation, and Continuous Variable QKDs (CV-QKD) to create what they call Quantum Resilience, i.e. the exploitation of the latest quantum technologies to build infrastructures resilient to present and future attacks and manipulations. The approach is defined by the company as crypto-agility, as it allows for rapid adaptation to potential new threats and, at the same time, to the demands of government regulators. One of its leading products, qProtect, is designed to leverage these technologies to protect critical and sensitive data during transmission and subsequent encrypted storage.

QuintessenceLabs

Austria-based **Quantum Industries** was founded in 2022 to bring to market a version of the QKD that exploits Nobel Prize-winning research in physics on quantum entanglement of photons even at great distances. The solution is called **entanglement Quantum Key Distribution (eQKD)**. This version of eQKD exploits the intrinsic properties of an entangled pair of electrons (polarisation-entangled photon pairs) to ensure efficient QKD over distances of up to 350 km. The team of scientists and researchers at Quantum Industries is convinced that the threats inherent in quantum computing will be relatively imminent. For this reason, the famous Cloud Security Alliance countdown, which predicts the emergence of a quantum computer capable of breaking the forms of encryption currently in use by 14 April 2030, is prominently displayed on their website's homepage.

Quantum Industries

In the field of quantum communications and QKD, the role of Europe, its companies and research centres is particularly relevant, as presented in Chapter 2. Within the European context, precisely in the field of QKD, **Italy** has carved out a particularly interesting role for itself due to its lively academic and entrepreneurial fabric.

Quantum Telecommunications Italy (QTI) was a pioneer in Italy for the design of quantum communication solutions and in particular for Quantum Key Distribution. The company was founded as a spin-off of the National Institute of Optics of the National Research Council (CNR-INO) in 2020. In 2021, during the G20 summit dedicated to science in Trieste, QTI achieved the world's first secure intergovernmental quantum communication involving three countries: Italy, Slovenia and Croatia.
QTI has developed a family of QKD devices, called Quell-X, consisting of two units working together (1 Alice unit and 1 Bob unit, as detailed in Chapter 1), designed to be implemented in telecommunications networks and for scientific applications. QTI also produces Quantum Key Management Entities (QKME) and Software Defined Network (SDN) applications to efficiently integrate and manage QKD in a network. QTI aims to provide product families that can be integrated with each other to create secure networks with QKD technology in a scalable manner.

Telsy, the cybersecurity and encryption company of **TIM Enterprise**, entered the capital of QTI in 2021. In 2024, in cooperation with **Sparkle**, the TIM Group's international telecommunication services company, it realised a Proof of Concept (PoC), for high-speed transmission of QKD-protected data over an existing network between two Sparkle data centres in Athens. The PoC demonstrated the feasibility and potential of the technology and equipment designed and manufactured by QTI. The company also participates in the national project Quantum Italy Deployment (QUID), and the European project EuroQCI.

QTI – Quantum Telecommunications Italy

levelQuantum is an Italian start-up that has patented a proprietary solution for an advanced form of QKD capable of overcoming some of the weaknesses of the approach currently used by many QKD device manufacturers. The system proposed by levelQuantum can integrate quantum detectors and promises secure information transfer even if the hardware components are compromised by some type of interceptor.

The levelQuantum architecture allows the integration of proprietary next-generation QKD technology directly into fibre optic networks. The keys can then be distributed using radio towers and drones in free space (free-space quantum communication) to increase coverage, or satellite networks to reach even larger or more distant areas (satellite QKD).

levelQuantum

A spin-off of the University of Padua, **ThinkQuantum**, specialises in the design and creation of discrete variable QKD devices (DV-QKD). The company specialises in the production of QKD hardware systems that can be easily integrated into metropolitan and regional fibre optic networks. ThinkQuantum is also developing a family of Quantum Random Number Generator (QRNG) modules for the ultra-fast generation of truly random number sequences, which can be used to increase the security of many types of IT applications in corporate and commercial environments. The company's strengths include its use of a European value chain and its roots in Italy.

ThinkQuantum

Random Power is an Italian start-up specialising in QRNG design. The company leverages quantum processes, specifically optical or electronic noise, to overcome the limitations of pseudo-random generators, which are widely used in IT today for communications security. Random Power has developed a diverse range of QRNGs, including highly compact, plug-and-play USB hardware devices, a rack-mountable module for existing servers and data centres, and a chip that can be easily integrated into security-critical systems.

Random Power

Future applications

Looking ahead, quantum technologies will be used in a variety of fields related to communications, in addition to those mentioned above and related to security and cryptography.
The exploitation of **quantum teleportation** protocols for the creation of a **quantum internet network**, characterised by much higher speeds and security than those achievable today, is particularly interesting. This form of "teleportation" does not involve the transport of matter from one point to another, but only information relating to a quantum system.

Teleporting particle properties

When we talk about **quantum internet**, the idea is not only to create networks capable of transmitting data faster and more securely than current ones, but also networks capable of effectively managing and transporting quantum information: therefore, this type of technology should be considered an enabler for the quantum networks of the future, which will be used to connect quantum infrastructure for data transmission, quantum sensors and even activities related to distributed quantum computing.

Studies to exploit entanglement between particles for ultra-fast and ultra-safe transmission of information over long distances have been ongoing for some time. A 2012 European Space Agency experiment confirmed the possibility of teleporting certain properties of particles with entanglement such as spin or polarisation. In the test this result was obtained over a distance of 143 km between the Jacobus Kapteyn Telescope on the island of La Palma and the ESA Optical Ground Station on the island of Tenerife.

Between 2012 and today, various research groups have demonstrated the feasibility of teleporting quantum information between increasingly distant points using different methodologies, including exploiting existing high-speed fibre optic networks.

In early 2025, for the first time worldwide, a group of researchers at the University of Oxford succeeded in demonstrating the quantum teleportation of logic gates, i.e. the unit components used to describe an algorithm. The entanglement between photons in two quantum computers two metres apart made it possible to quantum teleport an algorithm and make the two machines work together. The data were "teleported" with a fidelity of about 86%. This experiment can be considered an important step towards the creation of clusters of quantum computers that will be able to work together, albeit remotely, through **distributed quantum computing**. Furthermore, the same technology can be applied to create networks for the quantum internet.

Paving the way to quantum supercomputers

Experiments on real networks have highlighted the growing role of **quantum repeaters** and devices that extend the range of quantum signals. In concrete terms, these repeaters will play the same role in future quantum networks as signal repeaters for radio networks or fibre-optic channels do today. Quantum repeater technology is still largely in the theoretical or prototype development stage.

In Germany, the **Quantenrepeater.Net (QR.N)** project, funded with €20 million by the Federal Ministry of Research, Technology and Space (Bundesministerium für Forschung, Technologie und Raumfahrt) is investigating the best technologies and approaches for the practical implementation of quantum repeaters in existing communication networks and, looking ahead, in next-generation networks.
The project is led by Saarland University and involves a large part of the German academic world working in this field.

Quantenrepeater.Net - QR.N

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Qunnect has worked to make a reliable first generation of quantum repeaters. The company aims to become a technology provider to make the quantum communication network of the near future scalable. Qunnect offers a range of products designed to implement quantum communication on existing networks, particularly fibre-optic networks. The company's technology is also intended to be used in the fields of quantum sensing and quantum computing.

Qunnect

The Canadian company **Photonic** is designing hardware with various properties related to both quantum communication and quantum computing. The company is implementing a new silicon spin-photon interface architecture to create actual network nodes that can be used for quantum communications and distributed quantum computing, also in collaboration with major cloud computing groups such as Microsoft.

Photonic

Another Canadian company, **Quantum Bridge**, is testing a technology that could make quantum repeaters more reliable for telecommunications networks and easier to integrate than those being planned by many competing companies. Quantum Bridge is designing an all-photonic quantum repeater that does not contain quantum memories in order to reduce costs and simplify the repeater structure. In the future, the product should enable very long distances to be covered without significant quantum signal loss.

Quantum Bridge

Hybrid products are likely to emerge in the near future that combine quantum teleportation with existing technologies and networks in order to manage the transition phase between one technology and another. Interest in the quantum internet is considerable. The most immediate advantages include transmission speed and security, to which improved **energy efficiency** could also be added. In fact, this technology could enable the creation of data transmission networks with less energy impact, especially over long distances.

3.3 Quantum Computing

Among today's quantum technologies, quantum computing is probably the best known in the media.
Chapter 1 presented some of the fundamental characteristics of this technology. Attention, investment and programmes dedicated to the creation of quantum computers are growing worldwide. In addition to the analysis of clusters, ecosystems and their characteristics presented in Chapter 2, it is interesting to clarify the main motivation behind this industrial and scientific hype: quantum computers promise to revolutionise data processing in the near future with significantly higher capacity, speed and energy efficiency than the High-Performance Computing systems available today. The **large data processing capacity** will allow huge amounts of information to be analysed and more complex simulations to be carried out with potentially disruptive scientific and industrial spin-offs (discussed in Chapter 4).

The creation of quantum machines involves writing **special software** and, in some cases, devising **new programming languages**. Many companies, both large and small, are working hard on this, proposing very different approaches, ranging from the creation of proprietary platforms to the use of well-known and widespread programming languages such as Python. A major limitation in this regard lies in the lack of standardisation due to the fact that quantum computing is still in the prototype phase. Software is discussed in more detail in Chapter 4. The same chapter also deals in detail with access to quantum machines via the cloud.

Regarding the topic of **sustainability**, which is increasingly relevant in the current geo-economic context, quantum computers could play a significant role, positively impacting the consumption of critical resources such as energy and water, which are consumed in abundance by traditional data centres dedicated to cloud computing and artificial intelligence.

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According to a report by MIT Technology Review published in May 2025, the consumption of these supercomputing centres exceeded the threshold of 200 terawatt-hours of electricity in 2024, equivalent to the consumption of an entire country such as Thailand with 72 million inhabitants. Although quantum computing is not yet considered among the potential solutions, it is nevertheless reasonable to assume that the second quantum revolution currently underway could play an important role in reducing CO_2 emissions from applications that require a lot of computing power.

We did the math on AI's energy footprint. Here's the story you haven't heard

The point in time when a quantum computer will be able to solve a problem that is intractable for a classical computer is generally referred to as **quantum advantage**.

Many large companies and research groups have been working in this direction for years. In 2019, an initial theoretical demonstration of this potential computational advantage was achieved during a test on Google's *Sycamore* quantum processor. Sycamore, in that specific and defined case without any real practical application, was able to compute the result much more quickly (in the order of a billion times) compared to IBM's *Summit* system, the fastest supercomputer in the world at the time. Google then declared that it had achieved so-called **quantum supremacy**. Unlike a more complete quantum advantage, quantum supremacy only attests to the superiority of a quantum computer over a traditional one in solving a single task.

Quantum supremacy using a programmable superconducting processor

#use case
Quantum Supremacy

Quantum supremacy, as defined by John Preskill, a theoretical physicist at the California Institute of Technology, is the point at which a quantum computer achieves the ability to solve a task, useful or otherwise, that a traditional computer is unable to do within a reasonable time frame. The purpose of this goal is to demonstrate, purely and empirically, a concrete advantage in the ability to calculate.

#video
Quantum Computing con Simone Severini (Amazon Web Services)

The test carried out by Google in 2019 was a simulation of random quantum circuits performed in two minutes and thirty seconds, which Summit was thought to have taken millennia to complete. Subsequently, IBM downplayed Google's claim, stating that thanks to improved algorithms, a traditional supercomputer would be able to complete the same simulation in a matter of days. This episode showed that quantum supremacy is not just a theoretical issue, but a concrete and competitive technological challenge. Since that experiment, the scientific community has also launched multiple debates to clarify the issue. As pointed out by experts in the field, Google probably used the term quantum supremacy for marketing purposes as well.

#video
Quantum supremacy: A three minute guide

The achievement of quantum advantage will represent a geopolitical and industrial turning point. Governments have begun to invest heavily in this field over the last five years. The United States has launched the National Quantum Initiative, China has allocated funds to the Quantum Science Initiative, and the European Union has launched the Quantum Flagship programme. All these initiatives aim to expand scientific capabilities and promote industrial progress. On the other hand, competition is also fierce in the private sector, where Big Tech companies such as Google, IBM and Microsoft are accelerating their investments, making quantum technology one of the most promising challenges of the 21st century. This very race for quantum advantage highlights the great potential for development of this technology and how high expectations are. Quantum technology as a strategic element for government and private public investment is explored in Chapter 2.

From a technological implementation perspective, quantum computers still need to solve the major problem of **error correction** in order to ensure that calculation results are always reliable.
Many quantum computers currently produce error rates of around 10^{-3} (i.e. 1 error per 1,000 operations per unit of time). In addition to the limitation of error correction, these machines also face a manufacturing challenge related to the ability to produce reliable qubits, control software, and the hardware infrastructure necessary for the machine to function. The fundamental step that leads from a laboratory demonstration to a concrete advantage is a reduction in the so-called **physical error rate per operation**: the correction threshold should be less than **10^{-4}** (**i.e.** 1 error per 10,000 quantum operations).

Reducing the error rate to reach the Quantum Advantage

At the time of writing this report, the process is still ongoing and, although some prevailing technologies exist, it will take time to reach shared standards for the creation of quantum computers that are truly usable and can be integrated with existing technological infrastructures. Opinions as to when and how these error rates will be corrected vary. In principle, this threshold is expected to be reached around 2030. In fact, many scholars agree with the estimate presented in a 2019 study by the US National Academies of Sciences, which predicted a time frame of about 10 years.

Other researchers predict a significant impact from these computers even before this threshold is reached, but from this point of view the debate is open.

At present, it can be said that experiments in recent years, and in particular since 2019, have shown that the advantage of quantum computers is not only potential but real. However, it is still early days to say that this tech is ready to hit the market. In order to make a quantum computer truly implementable, it is therefore necessary to reduce the physical error rate per operation and increase the number of usable qubits. Overcoming what is known as the **fault-tolerant threshold** of these two parameters, above which the results are not considered reliable, remains the most important obstacle to ensuring that quantum computing truly revolutionises the industrial and scientific sectors in which it can be used.

In the field of quantum computing, the concept of **MegaQuops** (a million quantum operations), i.e. the possibility of performing a million reliable quantum operations before errors render the system unreliable, is increasingly mentioned. The **quops - quantum operations -** is the quantum equivalent of the **flops - floating point operations per second** in the classical domain.

Many companies consider the threshold of one million quantum operations to be the turning point for implementing algorithms that have a real impact on solving certain practical problems that today's supercomputers struggle to address, for example due to excessively long processing times. The study of protein folding in biomedical research, the discovery of new materials never previously theorised, and the optimisation or evolution of complex systems in the scientific or industrial fields are often cited as prime examples.

Towards the MegaQuop finish line

The achievement of MegaQuop is often announced in the roadmap for the development of quantum technologies presented by large groups or start-ups. Most companies believe that this goal can realistically be achieved by 2030 or, in any case, by the early years of the next decade. The importance of overcoming this threshold justifies substantial investments being made by governments and major industrial players at an international level.

Engineering approaches to quantum chip design differ in terms of scalability, speed of execution and coherence time:

Qubit engineering technology	Scalability	Speed of execution	Coherence time
Superconductors	+++	+++	+
Trapped ions	+	++	+++
Photonic	++	++	+++
Neutral atoms	+++	++	++
Silicon spin	++	++	+
Topological	+++	+	+++
Nitrogen-Vacancy Centre	+	+	++

Scalability = the ability of a quantum technology to increase the number of quantum elements (qubits or sensors) without compromising the overall stability and performance of the system, ensuring the technical and economic feasibility of the process.

Speed of execution = the speed at which a quantum system can complete quantum operations, determined by the number of quantum logical operations that can be performed per unit of time.

Coherence time = the time interval during which a quantum state maintains its quantum properties (superposition and entanglement) before decoherence compromises the information, thus representing the time limit within which the system can perform reliable operations.

Superconducting qubits

Superconducting qubit technology operates at extremely low temperatures, close to absolute zero. This technology is currently considered the most scalable from an industrial point of view, thanks to certain points of contact with technologies developed in recent decades for non-quantum electronics on solid-state circuits. For this reason, it is the technology platform chosen by many large companies and some start-ups to build scalable quantum processors, thanks to the experience gained in solid-state electronic circuits.

IBM immediately carved out a pioneering role for itself in the study and development of quantum computing with superconducting technology. IBM is building a real ecosystem related to quantum computing that integrates hardware, software and the cloud component. Since 2020, the computing giant has been designing and building a series of increasingly high-performance quantum processors, accessible to researchers and developers through an IBM cloud (already available since 2016). Starting in July 2025, the system changed platforms, upgrading to the latest hardware and software available.
IBM chips have come out fast over the last five years. In 2024, the 156-qubit chip *Heron* was launched, capable of handling 5,000 two-qubit gates (logical operations). According to information published by IBM, the new processor has greatly increased computing capabilities compared to the previous generation. The new system is seamlessly integrated with the *Qiskit* software development environment, designed to facilitate the writing and execution of quantum software for scientific and application purposes. The company's focus today is on error correction. IBM is regarded as the industry leader in the field of quantum systems, in their commercialisation through cloud access and in their promotion: IBM continues to make agreements and promote the installation of its quantum systems at public, research and private companies globally. IBM's roadmap envisages the creation of operational and functional quantum systems for various applications by 2030.

IBM Quantum is building a large-scale, fault tolerant quantum computer

Google is another key global player in the development of next-generation quantum processors. In 2019, the 53-qubit Sycamore processor enabled the company to announce the achievement of *quantum supremacy*. Since then, the company has focused on developing successive generations of processors and reducing errors. In 2023, Google demonstrated the concept of quantum error correction, according to which it is possible to reduce system errors by increasing the number of available qubits: this was achieved with the 105-qubit *Willow* processor. In the technical documentation describing the capabilities of the Willow processor, it is stated that "Estimated time on Willow vs. classical supercomputer" is "5 minutes vs. 10^{25} years" to perform a specific algorithm.

#video
Demonstrating Quantum Error Correction

Google is pursuing a holistic approach to quantum computing research, investigating various types of technology and a strong integration with the software component needed to compile and run quantum software. Google has released *Cirq*, an open source Python library for programming quantum computers. In addition, Google is investing in other technologies and companies to manufacture quantum chips. In particular, in 2024, it invested in QuEra, which specialises in the research and development of quantum chips with neutral atoms. In the short term, i.e. by the end of this decade, Google aims to build actual quantum data centres to offer its customers and scientific research enormous computing power for applications related to materials physics, biomedical research and simulation, big data management for the financial sector, and all those activities that could benefit from this enormous computing power.

Explore Google Quantum AI

Founded in 2013 in California, **Rigetti Technologies** was one of the first start-ups to focus on building a quantum computer with superconducting qubits and the related software for managing the machine. Rigetti built a factory for the mass production of quantum chips, the first in the industry, called *Fab-1*. The *Novera™* 9-qubit Quantum Processing Unit, marketed in 2024 starting at $900,000, is manufactured here. At the end of 2024, the 82-qubit Ankaa-3 processor was presented. Rigetti's quantum computers are available through a proprietary cloud platform and also through other business cloud platforms.
Rigetti is working to reduce the error threshold of its processors and the number of available qubits, with new releases expected between the end of 2025 and the first half of 2026. The company is one of the few in the world to have a true full-stack capability, integrating the design and implementation of hardware, software, programming languages and cloud platforms.

Rigetti developed a quantum instruction language called *Quil*, APIs to facilitate integration with other software and platforms, creating an integrated and scalable hardware and software ecosystem. This approach is also designed with the future in mind, to provide companies and research centres accessing quantum technology today with future-proof resources.

Rigetti Computing

In Europe, the leader in this type of technology is **IQM Quantum Computers**. Founded in 2018, the Finnish company has created two families of quantum computers that it is already marketing globally. IQM develops all the components that make up a quantum computer to provide the entire turnkey infrastructure to customers, with an on-premises approach. As of October 2025, IQM has raised a total of $592.18 million in funding.
The company built Europe's only end-to-end quantum chip factory in Finland and announced a second one in 2024 in France to increase its production capacity. Up to 20 quantum computers per year are manufactured and assembled in the same plant. In addition to computers, IQM also offers quantum computing services via the cloud, thanks to a Quantum Data Centre in Munich, Germany, built for the purpose.
IQM proposes a roadmap similar to that of other manufacturers, expecting to reach quantum advantage by 2030, and then to achieve fault tolerant quantum computers with 1 million qubits. Today, the company has a very precise strategy of business proposals. The first with the *Spark* quantum machine proposes a computing power of 5 qubits. Spark is mainly designed for research centres and universities. Italy's first commercial quantum computer, inaugurated in May 2025 by the Politecnico di Torino, the LINKS Foundation and INRiM in Turin, is a processor of this model. The second, high-performance family is called *Radiance*: computers in this category can count on 20 qubits that can be increased to 54, and in the near future expandable to 150.

IQM Quantum Computers

Another relevant player at European level is **Oxford Quantum Circuits (OQC)**. The British start-up has engineered a new type of quantum chip that develops over three dimensions. The *Coaxmon* chip has a structure designed to maintain high qubit reliability while improving system scalability, yet retaining considerable structural simplicity. Coaxmon is the basis of the quantum computer dedicated to businesses, *Toshiko Gen 1*, with a computing power of 32 qubits. OQC follows the commercial offering of many quantum machine manufacturers, selling both computing power via the cloud, with a commercial approach of Quantum Computing as a Service, and the quantum machine itself.
OQC sees the development of hybrid machines as an opportunity for growth in the coming years, where the quantum

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component complements the classic component of a supercomputer for high-performance computing, with an approach defined as "quantum colocation". The company received significant Series B funding in 2023, considering the European context, for a total of $100 million, to finance its growth in terms of research and production capacity.

Oxford Quantum Circuits

SeeQC is a US start-up working on a hybrid approach to quantum chip manufacturing. SeeQC has patented a technology called *Single Flux Quantum (SFQuClass) processors* for the production of quantum System-on-a-Chip. This technological approach allows for the integration of both qubits and the circuits needed to manage them, greatly simplifying the cryogenic structure required for the machine's thermal management. The system for handling information input and output is also greatly simplified. The result should translate into a significant reduction in manufacturing costs, according to some estimates up to 97%, and energy consumption.
SeeQC has built a foundry to manufacture its customised quantum chips according to its customers' specifications. The in-house foundry allows it to control the entire supply chain to ensure production quality and avoid dependence on external suppliers. SeeQC's hardware + software platform lends itself well to integration into hybrid computers supporting classical supercomputers and to the creation of application-specific integrated circuits in industry or research. SeeQC has established collaborations with laboratories in the United Kingdom and Italy, where in 2023 it demonstrated its ability to build a full-stack quantum computer in its laboratories in Naples.

SeeQC

On the other hand, Canada's **D-Wave Systems** has taken a different path, embracing a type of quantum computation that is not universal, but oriented towards solving optimisation problems, called adiabatic computation. D-Wave brings to the market *Advantage2*, a so-called Quantum Annealer, i.e. a special type of quantum computer that exploits the phenomenon of Quantum Annealing, a quantum strategy for quickly solving complex problems by searching for the best solution among numerous options. The quantum processing unit in question contains over 4400 superconducting qubits and is also accessible via a dedicated cloud service. D-Wave was among the first companies to announce the quantum supremacy of its quantum machine in solving a real-world computational problem in early 2025.

D-Wave Systems

Superconducting qubit technology is also being developed by other technological players in Asia, where Japan and China are pursuing various activities at both the research and industrial levels.

Trapped-ion qubits

Another type of qubit consists of **ions trapped** in electromagnetic fields and manipulated using high-precision lasers. These qubits are generally valued for their uniformity due to the use of atoms of the same element. This feature makes these machines particularly reliable. However, the use of lasers makes them complex to build and scale up to large sizes. This approach results in slower speeds compared to other types of quantum computers, such as those based on superconductors.

IonQ develops quantum computers in ultra-high vacuum, controlled by high-precision laser pulses. The hardware platform performs very well in terms of stability and accuracy, with high coherence times and fidelity close to 100%. In 2024, the company announced that it had exceeded the three 9's, i.e. a threshold of 99.9% of fidelity in two-qubit gates on a prototype next-generation barium ion quantum processor. For IonQ, this is a fundamental step towards managing physical error below the fault-tolerant barrier.
The company adopts an internal metric for evaluating the computing power of its machines called Algorithmic Qubits (AQ) that merges several parameters, including physical qubits. With this classification, IonQ's flagship processor now reaches 35 AQs. A new version with 64 AQs is expected to be available by early 2026: according to the company, the new *IonQ Tempo* processor will perform well enough to guarantee a commercial advantage for certain types of applications.

IonQ

The merger of Honeywell Quantum Solutions and Cambridge Quantum in 2021 gave rise to **Quantinuum.** The company is one of the world's largest players in trapped ion design and computing. Quantinuum has offices in the US, UK, Germany and Japan, enabling it to integrate the entire supply chain, from quantum chip design to the production of the electronics and refrigeration required for quantum machines. Quantinuum produces a family of quantum computers, the H-Series. The new H2 generation, released in 2024, achieves a two-qubit fidelity of over 99.7%. The company is also working on the integration of quantum computers into classical supercomputers.
In 2025, Quantinuum implemented a hybrid solution in the quantum computer installed to complement the classical supercomputer at the Japanese research centre RIKEN. The hybrid machine will be used for highly complex applications, particularly in the energy sector. Quantinuum markets other quantum products, including a quantum random number generator called *Quantum Origin* and a software platform for advanced simulation of chemical compounds and materials physics.

Quantinuum

Universal Quantum is a spin-off from the University of Sussex that has developed a modular trapped ion platform with proprietary technology designed for scalability to millions of qubits. The special construction reduces cabling complexity and simplifies the overall architecture, again with a view to favouring scalability. Universal quantum has entered into a collaboration with the German Aerospace Centre (DLR), winning a €67 million tender to build two next-generation quantum computers at the DLR headquarters in Hamburg. The first computer will be a single-chip demonstrator with the entire quantum logic integrated, while the second will adopt a modular multi-chip architecture, with up to 100 qubits available. The two systems are characterised by high reliability, low power consumption and a simplified cryogenic architecture. Due to their location at the same site, they will be used by researchers and companies for comparison and testing between the two quantum technologies.

Universal Quantum

Photonic qubits

The **photonic** approach involves the use of chip-based qubits capable of manipulating and managing individual photons. Photons offer the advantage of having a very high **coherence time** during which their quantum properties are maintained, making them ideal both for creating qubits and for transporting information over long distances. Developments in this particular field are being made rapidly, providing access to increasingly high-performance photon sources and integrated chip systems.

PsiQuantum has a very clear mission: "*To build and deploy the first useful quantum computers*". PsiQuantum is working on the hardware and software components for fault-tolerant quantum computers with one million logical qubits. The company places great emphasis on the concept of useful quantum computers, since it believes that the quantum computers with a real impact will be those that are easily achievable and usable. For this reason, the company is developing a series of technologies and production facilities for silicon photonic circuits. For the same reason, the programming language for the algorithms is Python, which has been known globally for years. PsiQuantum's vision has convinced investors, who have so far invested around $1.3 billion in the company.

In early 2025, PsiQuantum announced the *Omega* processor, a photonic quantum chipset designed for mass production. The chipset will be powered by a new-generation cryogenic unit with a cubic form factor, characterised by greater energy efficiency and simplicity. The company is building two data centres to test the capabilities of this technological solution, one in the United States and one in Australia.

PsiQuantum

Xanadu was founded in Canada in 2016 to develop photon-based quantum computers. Xanadu's proprietary technology exploits compressed states of light, known as squeezed states. The company has been conducting a series of tests since 2022 to prove how good its quantum technology is compared to classical High-Performance Computing systems. Xanadu is industrialising a 12-qubit quantum computer with photonic technology: *Aurora*. The system is designed to operate at room temperature, with a modular architecture that can be easily expanded and integrated with existing supercomputing systems. Xanadu also works on the software component of its quantum systems: it has developed an open-source library for writing, testing and developing hybrid quantum-classical algorithms called *Pennylane*.

#video
Introducing Aurora: First modular, scalable and networked quantum computer

03 / Technologies

Quandela is a French company that has developed a hardware, software and cloud platform to offer quantum computing services, becoming a full-stack manufacturer in the photonic quantum equipment segment. The chip *Prometheus* exploits quantum dot technology to emit single photons that are then used as flying qubits. In 2022, Quandela launched a cloud in which researchers and companies can access an open-source framework for software development, the design of new quantum algorithms and the execution of simulations. The technologies developed by Quandela were used to build a modular quantum computing platform called *Mosaiq*. The system is modular and customisable, with an architecture scaling from 6 to 24 photonic qubits. In 2024, Quandela presented a roadmap that envisages the creation of the first logical qubit (without errors) by 2025 and the implementation of a quantum networking system connecting multiple quantum computers by 2028. It also aims to make a fault-tolerant photonic quantum computer available by 2030.

Quandela

Neutral-atom qubits

Another technological approach involves the use of non-ionised atoms, cooled and controlled by appropriate optical instruments to obtain **neutral-atom qubits**. This solution provides a good balance between scalability and consistency. Relatively few companies worldwide are developing this technological approach, with a significant concentration in the United States, where QuEra, Atom Computing and Infleqtion stand out for the funding they have received and their research activities.

QuEra is based near Boston in the US and stems from research activities carried out by MIT and Harvard University. QuEra's qubits are based on neutral atoms of rubidium, cooled to temperatures close to absolute zero and controlled via high-precision lasers. The company is developing both an analogue and a digital quantum computer, both available on a proprietary cloud platform as well as on AWS. The flagship product is the 256-qubit *Aquila* processor, currently publicly available for the design and testing of quantum algorithms. At the beginning of 2025, QuEra received $260 million in funding with Google as one of the main backers.

QuEra

Atom Computing uses a similar approach, aiming to build an extremely scalable quantum computer. The company is collaborating with Microsoft, demonstrating at the end of 2024 its ability to create and manage 24 logical qubits of entangled neutral atoms, a result never achieved before. Atom Computing is designing a next-generation quantum computer, still in the study phase, with more than 1,000 qubits.

#video
Atom Computing Technology Advantage

Infleqtion works on various quantum technologies. In the area of computing, it is designing and building easily scalable neutral atom systems. It has set up important partnerships with industry players, in particular with NVIDIA, demonstrating the feasibility of quantum simulations for research into new materials using the CUDA-Q platform. The company has adopted a strategy to implement new hardware and related software to achieve a fault-tolerant quantum computer with 100 qubits.

Infleqtion

At the European level, the French **Pasqal**, a spin-off of the Institut d'Optique in Paris, is the most interesting case. Pasqal is developing Quantum Processing Units that are strongly oriented towards integration with classic, highly scalable High Performance Computing systems. The *Orion Gamma* system has approximately 140 qubits using neutral atom technology, while its successor, *Vela*, due to be delivered in 2027, is expected to exceed 200 qubits. Pasqal has already set up numerous industrial partnerships and its quantum computers are available via cloud services provided by Google and Azure. Pasqal aims to demonstrate the ability to manage logical qubits without error by 2026, with a tight roadmap to achieve a machine with 10,000 qubits by 2030.

Pasqal

Qubit Nitrogen-Vacancy Center

The technological approach that exploits **Nitrogen-Vacancy Centres**, where **qubits correspond to point defects in the crystal lattice of a diamond**, offers an interesting alternative. The main advantage of qubits made in this way lies in their high stability even at room temperature: therefore, no equipment is needed to maintain the quantum machine at cryogenic temperatures. However, these systems are theoretically more complex to scale up from an industrial point of view precisely because they are based on impurities in crystal lattices such as those of synthetic diamonds, which are complex to manage on a large scale.

Quantum Brilliance is an Australian company founded in 2019 that develops quantum computer hardware and *quantum accelerators*. These accelerators exploit nitrogen-vacancy qubits to create co-processors that integrate into existing machines for High Performance Computing. Therefore, the system is designed to work in synergy with existing supercomputers, optimising calculations and processes where the quantum approach can lead to a real advantage for users. The systems are extremely compact as they can operate at room temperature and can be integrated into standard data centre racks. Quantum Brilliance's products currently have few qubits, but there is a roadmap to increase this number by the end of the decade.

Quantum Brilliance

SaxonQ is a spin-off of the German Felix Bloch Institute of Solid State Physics at the University of Leipzig. The start-up project focuses on simplifying the structure of the quantum machine to reduce its weight, size and operational complexity. The decision to use NV quantum qubits allows SaxonQ's technology to be implemented in many operating environments. The start-up is working on a portable quantum computer suitable for realistic and operational use cases that will be characterised by ease of use and the ability to operate at room temperature, thus ensuring limited energy consumption. A first demonstration took place in April 2025 at the Hannover Messe with a demo that confirmed the real-time image recognition capabilities of such a portable quantum computer.

SaxonQ

Emerging technologies

Other technologies for the production of quantum computer chips are being developed by large industrial groups to respond to specific market demands that are well suited to technological niches and, in part, to exploit the technological advantage that some companies have in specific markets. US semiconductor giant Intel falls into this category. **Intel** is investing in technology for the production of **silicon spin qubits**, where the qubits correspond to the spins of electrons confined in semiconductor structures. Intel has decided to focus on this technological approach in order to fully exploit its enormous scientific, patent and industrial background in the design and manufacture of silicon chips.

Intel Labs is working on the design of quantum machines from both a hardware and software perspective, like other large groups and similar start-ups. Intel's *Tunnel Falls* quantum chip is made using the same extreme ultraviolet (EUV) lithography technology currently used in the production of commercial transistors with CMOS technology. Specifically, Tunnel Falls contains 12 qubits. Intel is aiming for the greatest possible scalability to accelerate mass production and fully exploit its technological and patent portfolio. On the software side, the *Intel® Quantum SDK* is being distributed to help companies, research institutions and scientists exploit the potential of quantum machines. The SDK offers an optimised environment for writing and testing applications, combined with an intuitive interface. Intel is proactively working to build a dedicated quantum ecosystem, particularly in the United States, where the chip has been distributed to selected institutions, research centres and universities.

Discover Quantum Computing

03 / Technologies

The possibility of creating **topological qubits** (see Chapter 1) using exotic quasi-particles for qubits has recently emerged. This area of quantum research is at a lower level of development than those presented previously: the technology is therefore still in a theoretical phase, with few players involved globally compared to other areas of quantum computing. However, from a theoretical point of view, the use of topological qubits brings some interesting advantages, in particular an intrinsic error tolerance.
In this particular sector, **Microsoft** is the main player. The US multinational presented the first quantum chip with topological qubits, the Majorana 1, in early 2025. The name of the chip is a tribute to the Italian physicist Ettore Majorana who first theorised about these quasi-particles in the 1930s. The chip structure is very complex, with a combination of semiconductor and superconductor materials. The chip developed a topological nature upon reaching temperatures close to absolute zero. The first version of Majorana 1 contains 8 qubits, with the potential, according to Microsoft, to scale up to a million qubits on a single chip. The Majorana 1 chip was designed as a quantum accelerator for operations to be carried out in synergy with classic High Performance Computing machines, in which only certain operations that can benefit from a quantum approach are delegated to the accelerator.

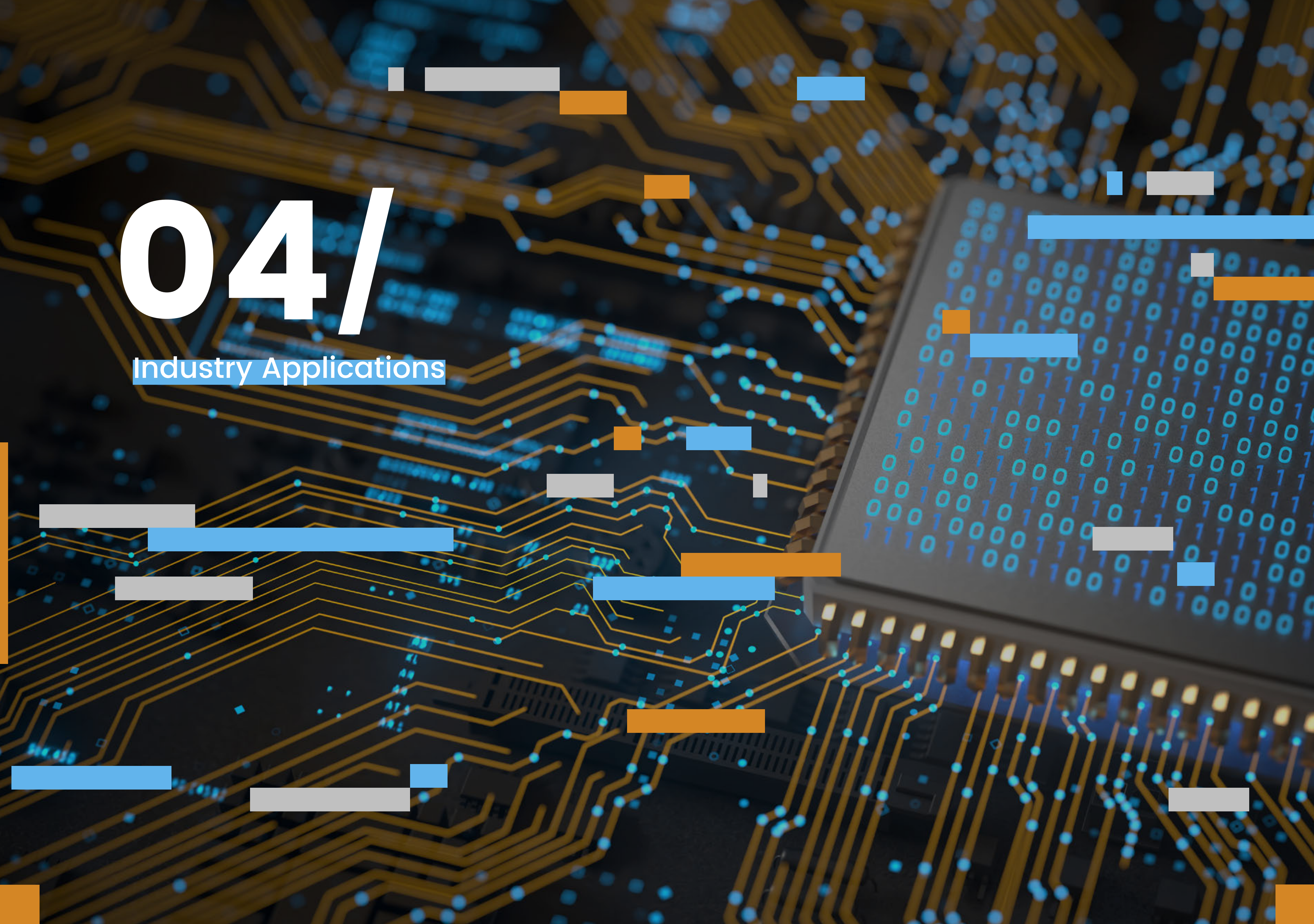
#video
Majorana 1 Explained: The Path to a Million Qubits

The US tech giants, particularly cloud service providers Google and Microsoft, have recently been joined in the arena of research into new quantum processors by **Amazon**. In 2025, Amazon Web Services announced *Ocelot*, developed by the internal team at the AWS Center for Quantum Computing at the California Institute of Technology. Ocelot uses a new type of design based on **cat qubits**, so called because of Schrödinger's experiment, which is the basis of the theory explaining how they work. This configuration should make error correction easier and more feasible. In fact, Ocelot promises to drastically reduce the cost of correcting and mitigating such errors thanks to its approach, which the company calls "*error correction built in*", paving the way for the commercial use of quantum technology.

Amazon announces Ocelot quantum chip

04/

Industry Applications



In recent years, quantum technologies have been the subject of much discussion about their potential positive impact in certain industrial and economic sectors.
The debate intensified in 2019 with Google's claim of quantum supremacy (see Chapter 3). The previous chapter presented the target market for the three main quantum technologies from which new industrial applications are emerging, namely quantum sensing, quantum communication and quantum computing.

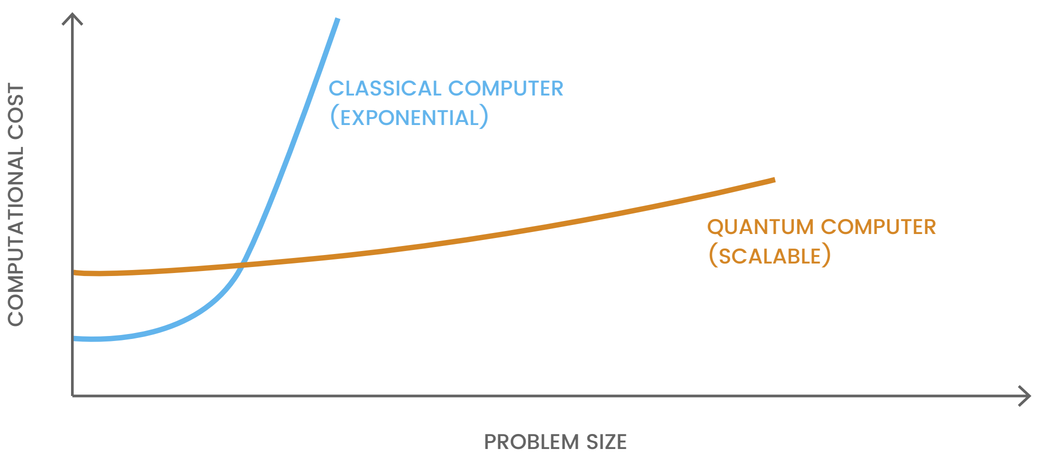
The scope of application for these technologies is gradually expanding to include industrial sectors other than those for which they were originally conceived and designed. This trend is common to many emerging technologies capable of solving complex problems: for example, consider the use of graphics cards (GPUs), initially designed to improve the fluidity of video images, now widely used in machine learning and artificial intelligence.

In terms of the cross-industry applicability of quantum technologies, while quantum sensing and quantum communication naturally focus on specific sectors (respectively biomedical, military and geodetic for the former, cybersecurity and telecommunications for the latter), quantum computing, on the other hand, makes it possible to tackle problems that cannot currently be tackled within a reasonable time frame and at a reasonable cost in a variety of industrial sectors, from chemicals and pharmaceuticals to logistics, automotive and energy supply, and financial services.

The varying degrees of technological maturity, the specific characteristics of each industry and, finally, the availability of funding have a significant impact on the cross-industry use of quantum technologies.
Quantum computing best expresses its potential compared to traditional computing systems in highly complex contexts because of its high efficiency, which translates into lower computational costs.

Potential of Quantum Computing

Qualitative comparison of the computational cost of simulating a quantum system with a classical computer vs. a quantum computer



Healthcare, chemistry and materials science are considered among the industrial sectors where the potential of these technologies will materialise most rapidly.

These are very broad fields, featuring a large number of enabling technologies for their development, both from a research and industrial production perspective. For these three sectors, quantum technologies will have a disruptive impact in the medium term (5–10 years): quantum sensing enables new ultra-precise measurement systems, while quantum computing opens the door to extremely complex and detailed simulations that can be performed quickly or even almost in real time.

Computing power will become an enabler to create new businesses and accelerate the discovery of metabolic processes, biological interactions between molecules, and **new drugs and materials**. Furthermore, the combination of several technologies such as quantum sensing and computing will make it possible to create **digital twins of complex objects**, including from a biological point of view, in order to better understand their functioning, evolution and thus be able to intervene with new therapeutic or advanced predictive maintenance approaches.

Energy and transport networks will also benefit from quantum technologies to increase efficiency, safety and resilience in stressed conditions. In particular, quantum computing promises a significant impact in terms of **sustainability**, thanks to the optimisation of complex systems involving a large number of variables such as, for example, those related to managing energy and transport networks. Quantum computing will also make an important contribution to the optimisation of transport and logistics, improving **route planning and traffic management**, dynamic allocation of resources in complex systems and the synchronisation of supply chains. The direct benefits will be tangible: reduced operating costs, increased reliability and lower logistics-related emissions.

Finally, financial institutions, both public and private, were among the first to recognise the disruptive and transformative role of quantum technologies due to their impact on security and industry resilience. Interest has focused on quantum communication, due to its relevance in developing **advanced cryptography** systems, and on quantum computing, as a useful tool for improving the analysis of large volumes of data and strengthening financial risk management mechanisms.
The use of quantum communication mostly concerns the implementation of secure protocols and the adoption of Quantum Key Distribution techniques to protect information flows. Quantum computing, with its computing power characterised by flexibility and speed of execution of operations, is seen as a new technological step for optimisation processes, fraud detection, anti-money laundering activities and analysis of large databases to promote monitoring or investment activities.

#use case
Quantum Computing as a Service

Quantum Computing as a Service (QCaaS), leveraging Cloud Computing infrastructures, represents an enabling service for access, experimentation and development of quantum computing, especially in a fragmented technological environment where hardware availability is still rather scarce.
In this scenario, QCaaS enables companies, universities and research centres to test quantum algorithms and implement applications by remotely accessing real quantum machines or simulators, without the need to own on-site or manage physical hardware, which is still relatively expensive and complex to maintain independently.
Therefore, Cloud Computing breaks down barriers to entry, making quantum technology democratic and scalable. This approach allows companies of all sizes to compare the performance of different quantum hardware and to experiment with algorithms on multiple platforms without any particular vendor constraints.
However, it must be considered that the absence of common international standards is a significant obstacle to software portability and interoperability among different systems. Each provider adopts its own framework, languages and specific APIs (e.g. IBM's Qiskit, Google's Cirq, Microsoft's Q#), making code reuse and comparability between platforms difficult.

The three major cloud operators leading the QCaaS offering are:

- Google Cloud, which provides access to its Sycamore platform via Cirq, as well as IonQ, AQT and Pasqal, and high-performance quantum simulations
- Amazon Web Services (AWS), with the Amazon Braket service, which allows access to multiple quantum technologies from manufacturers such as IonQ, Rigetti, QuEra and IQM
- Microsoft Azure Quantum, which offers an integrated architecture for accessing quantum machines from selected partners (Quantinuum, Rigetti and Pasqal) and incorporates a development environment (Q#) focused on modularity and scalability

Amazon Braket – AWS Quantum Computing

Microsoft Azure Quantum

Google Quantum AI

The availability of these platforms as services not only accelerates experimentation and research, but also enables the creation of a growing ecosystem that includes start-ups, public laboratories, hardware suppliers and software developers. Thus, QCaaS becomes the infrastructural bond of a rapidly evolving sector, which does not yet have a predominant technology but holds great potential for transformation.

4.1 Healthcare, Chemistry and Materials Science

Chapter 3 presented companies and start-ups that are already using certain features of quantum mechanics to increase the precision and speed of medical analysis equipment. In general, quantum sensing is proving to be able to dramatically improve **the sensitivity of disease detection devices** and give rise to new forms of diagnostics capable of analysing and detecting biomarkers at very low concentrations that are often undetectable with traditional technologies.

Advanced diagnostics and research into new molecules

One example is the new forms of magnetic resonance imaging that exploit these phenomena to provide scans that significantly increase accuracy and detail, which are both essential for the very early diagnosis of degenerative, oncological, cardiovascular and metabolic diseases.

Quantum sensing is proving capable of measuring minute variations, often almost imperceptible by current standards, in magnetic, electric or gravitational fields, even at cellular level.

In general, the techniques conventionally used for detecting proteins and markers of various types (such as tumour markers) encounter intrinsic limitations due to the complexity of the physiological environment in which the scan is performed, because other fluids, such as blood, and other biological components are present.

The potential of new families of quantum sensors that use Nitrogen Vacancies (NV) in synthetic diamonds to overcome obstacles such as those encountered in *Debye screening*, where the charges of certain biomolecules cannot be detected beyond a very limited distance, is becoming apparent in this context. For example, these new sensors will enable the detection of microRNAs of key tumour biomarkers, increasing current diagnostic capabilities and potentially reducing the cost and complexity of these tests. The same technology, still under development, could be used to detect viruses in both neuroscience and advanced molecular biology.

The Swiss company **Qnami** designs, develops and manufactures sensors that exploit the NV of artificial diamonds at room temperature for extremely precise scans. The company is focusing on the creation of high-resolution scans for monitoring the weak magnetic fields emitted by biological tissues, clusters or individual cells, for diagnostic monitoring activities in various sectors, from neurology to everything that can be included in customised medicine. Qnami's nanoscale imaging technology can be used both in the biomedical field and for materials analysis. ProteusQ™ is Qnami's flagship product, a quantum microscope that can be used to analyse the magnetic fields of various materials.

Qnami

Besides Cerca Magnetics, presented in Chapter 3 and considered among the most promising in the field, other companies are developing devices for advanced monitoring of vital parameters.

MAG4Health is a French start-up that is developing new optical magnetometers, Optically Pumped Magnetometers (OPM), for very high resolution magnetoencephalography (MEG). OPM technology will enable the creation of compact, easily wearable devices with lower running costs than today's devices, including those using SQUID quantum technology that requires cryogenic temperatures in order to operate, leading to a corresponding increase in infrastructure costs.

MAG4Health

The healthcare sector will also benefit from quantum communication to manage sensitive data such as health data with more stringent levels of security and privacy. Although experiments have been launched in this specific area, their development is less advanced than in similar use cases in other areas such as the exchange of intelligence information or the management of financial transactions.

Quantum computing in healthcare, chemistry and materials will have an impact that many analysts predict will be disruptive and transformative. Competition from traditional High-Performance Computing systems already available, both in terms of computing capacity and, within certain limits, energy efficiency, represents a real challenge. However, quantum computing will be especially interesting in all those cases where highly complex simulations are required and in particular where synergetic use with Artificial Intelligence is envisaged.
The combination of these two technologies will enable all those calculations that are currently difficult to handle using "traditional" methods, or even impossible from a computational point of view, to be tackled efficiently in terms of energy consumption and execution times (see Chapter 3).
Quantum computing could prove particularly suitable for generating simulations, typical in pharmaceutical chemistry, characterised by a considerable number of variables with a very high degree of accuracy.

Therefore, this approach will revolutionise the following areas:

- Simulations for the discovery of new drugs, molecules, chemical compounds and materials
- Creation of advanced digital twins of complex biological systems for virtual testing and/or monitoring of real patients
- Folding of proteins and their evolution
- Advanced machine learning for monitoring vital parameters or analysing big data from medical examinations, diagnostic images and clinical databases

The report *The convergence of healthcare and pharmaceuticals with quantum computing: A new frontier in medicine* by the UK National Quantum Computing Centre (NQCC) points out that quantum computing holds great potential for performing molecular simulations and aiding the discovery of new drug compounds. The same technology can have a practical application in the optimisation of clinical trials, which, by their very nature, are extremely complex to manage, due to the clustering of patients and the analysis of the data obtained.

The potentials presented in the UK institution's report are shared with other sectors that require similarly complex and computationally intensive simulations. In addition to the limitations dictated by a technology that is in many ways not yet mature and still in the development and standardisation phase, there is also the limitation of access to health and biomedical data, as well as the specialised skills required to make the use of quantum computing truly usable.

Quantum computing for healthcare and pharmaceuticals

IBM has long since invested heavily to become a full-fledged player in the field of quantum computing, from hardware to software, via the cloud and everything revolving around it. By 2029, IBM will build Starling, a new high-performance quantum computer. The company's press release describes it as a machine with exceptional performance "*To represent the computational state of an IBM Starling would require the memory of more than a quindecillion (10^{48}) of the world's most powerful supercomputers. With Starling, users will be able to fully explore the complexity of its quantum states, which are beyond the limited properties able to be accessed by current quantum computers.*" Among the intended uses for the new computer are the discovery of new drugs and research in the fields of chemistry and new materials.

IBM Sets the Course to Build World's First Large-Scale, Fault-Tolerant Quantum Computer at New IBM Quantum Data Center

Qubit Pharmaceuticals is working to create a platform that is able to exploit quantum technologies for molecular simulation. The French start-up is implementing a series of different but complementary technologies to achieve the realistic possibility of simulating how proteins and drugs can interact with the human body. The use of hybrid techniques combining High Performance Computing and quantum computing, together with new simulation models using synthetic data for molecular chemistry, will provide a level of accuracy that is not currently available. Qubit Pharmaceuticals thus aims to simulate the molecular and, in the future, even atomic events, to guide the development of new drugs, understand how to maximise the effectiveness of those currently available, and thus aim to usher in a truly customised medicine.

Qubit Pharmaceuticals

The Finnish start-up **Algorithmiq** is working on the design and implementation of new software solutions for the quantum simulation of molecules, the discovery of new molecules and drugs, and new materials and processes for the green transition. The company has created a Digital Quantum Interface that efficiently integrates computing power from traditional High Performance Computing systems and quantum machines.
Algorithmiq has designed a family of proprietary algorithms to search for new solutions in the field of chemistry. The start-up offers a multiscale approach that combines the best of the potential offered by quantum computing and Artificial Intelligence techniques to provide advanced modelling of the molecular mechanisms underlying interactions between drugs and their biological targets. The same approach is used for activities related to the discovery of new molecules and medicines.
The company has been collaborating with IBM since 2023. Algorithmiq's Tensor-network Error Mitigation (TEM) is now used in complex simulations to increase the quality of the results obtained and achieve an overall gain in the computational efficiency of IBM's quantum computers used for complex simulations.

Algorithmiq

Quantistry specialises in the design of software architectures for simulation in the fields of computational chemistry and research into new materials and molecules. The German start-up focused on building a platform that offers users a native cloud environment. The QuantistryLab platform takes a multiscale approach, from the atomic to the macroscopic scale, in the simulation of complex molecules and materials. It is also designed to offer a user-friendly environment for researchers. Quantistry combines the potential of machine learning with that of Artificial Intelligence to achieve quantum computing, in order to be able to provide, as soon as it becomes available, the so-called quantum advantage also thanks to existing collaborations with important industrial partners. Quantistry is focusing on certain industrial sectors where this type of simulation could play a significant role in bringing new products to market, such as energy storage and the development of new chemicals for batteries, the development of new metals, metal alloys and ceramics, catalysis, organic chemistry, optical materials and semiconductors, polymers and lubricants.

Quantistry

Government programmes to develop new materials

The US Government launched a programme in late 2024 aimed at harnessing the potential of quantum computing in the field of chemistry and materials with a focus on energy. The **Quantum Computing for Computational Chemistry program (QC³)** aims to create new methods and processes for the simulation of new chemistries and materials for certain industrial sectors such as catalysts, next-generation batteries and accumulators, and high-temperature superconductors for power transmission networks. Participating companies are committed to finding solutions that perform at least 100 times better than the systems currently used in industry in order to bring new approaches and methodologies to the market that can be considered truly transformative. To achieve this very demanding result requires the ability to push forward both new developments in quantum computing hardware and the development of error correction algorithms.

Quantum Computing for Computational Chemistry program (QC3)

The European research project **PASQuanS2 - Programmable Atomic Large-Scale Quantum Simulation 2.1**, active until 2026 and a follow-up to the PASQuanS project, aims to design and develop a new generation of quantum simulators for solving computational problems in the fields of chemistry, industrial optimisation and materials science. The project is one of the initiatives of the European Commission's so-called Quantum Flagship, designed to foster the emergence and expansion of quantum technologies within the European Union and its supply chain.
The PASQuanS2 consortium is led by the German research centre Max Planck with around 30 partners from all over Europe. The project will develop programmable quantum simulators capable of handling quantum machines with a computing power of up to 1,000 qubits at neutral atoms. The platform will be designed to allow the hardware and software to work in synergy with a view to scalability and flexibility, so that it can be easily adapted to different industrial environments. PASQuanS2 is supported by both public and private research institutions, as well as industrial partners, with a view to promoting efficient technology transfer and thus bringing the results of fundamental research to market more quickly.

PASQuanS2

4.2 Energy and Transport

Transport and distribution networks are a fundamental part of the way energy is not only produced but also supplied today, as they must adapt to renewable energy sources, such as wind and solar, which are by nature intermittent: hence the term **smart grids**, which are dynamic and adaptable in real time to the context in which they operate.

Quantum communications, particularly those based on Quantum Key Distribution, will contribute to the exchange of secure information within smart grids, which are now increasingly interconnected and, as a consequence, vulnerable to cyber attacks and cyberterrorism.

Securing electricity grids

In the US, start-up **Atom Computing** has entered into a strategic collaboration with the **National Renewable Energy Laboratory (NREL)** to apply quantum computing to power grid management. The aim is to optimise the automatic reconfiguration of distribution lines to prevent blackouts and reduce the response time to faults. Using a "**quantum-in-the-loop**" interface, researchers connect real-time simulations of the state of the power grid to a quantum processor to instantly solve energy routing problems. Compared to traditional methods, the quantum solution allows reactions in fractions of a second, ensuring greater resilience and sustainability.

Atom Computing

In 2025, **Toshiba Europe**, in cooperation with other European partners, published the results of a successful test where a **Quantum Key Distribution (QKD)** system was implemented on a fibre-optic network over 250 km long, using the advanced Twin-Field QKD protocol. The network transmitted quantum cryptographic keys at 110 bit/s **without the need for cryogenic systems**, making the solution more scalable and easier to integrate into existing infrastructures. This demonstration is particularly significant for the energy and critical infrastructure sector, as it paves the way for advanced protection of control and communication data in scenarios that are increasingly vulnerable to cyber attacks. The initiative shows how quantum technologies are no longer just theoretical, but ready for large-scale operational applications.

The optimisation of smart grids is a growing challenge. The connection of an increasing number of renewable plants to the transmission grids, which by their very nature are intermittent, poses considerable problems of grid management and balancing. The use of computing power generated by quantum computing will enable increasingly complex networks to be managed efficiently in the near future, boosting the resilience of electrical systems.
In particular, it is estimated that quantum computing will be able to provide a high-performance solution for solving the so-called **Unit Commitment Problem** (**UCP**), i.e. the problem of optimally choosing which energy production systems to activate depending on the grid load. Quantum computing will provide reliable results with very competitive time frames for evaluating which power stations to switch on. This type of application is being studied by various smart grid and power generation operators. Current systems mainly use heuristic algorithms, which are showing increasingly obvious limitations as the energy mix becomes more complex. The ability of quantum computing to handle complex calculations with many variables will enable new levels of optimisation, in particular by exploiting Variational Quantum Algorithms (VQAs).

The topic of optimising power grids, in particular with hybrid quantum-classical methods and algorithms, kick-started a collaboration in 2025 between **Classiq**, which deals with software for quantum computing, **Wolfram Research**, which focuses on computational computing, and **CERN's Open Quantum Institute**. The collaboration aims to propose solutions that exploit complex computational models that can provide highly reliable information and simulations to decision-making systems for smart grids. In this case, the focus is also on the replicability and true scalability of quantum and quantum-hybrid solutions, especially for UCP management, which will be tested in the coming years.

Classiq and Wolfram Join CERN's Open Quantum Institute to Develop Quantum Optimization for Smart Power Grids

Among projects touching on similar topics, the **Grid Research, Integration and Deployment for Quantum (GRID-Q)** project, funded by some US government agencies in 2024, brings together quantum laboratories and industrial players, such as IonQ, to research and test new quantum technologies for optimising smart grids, bringing together quantum sensing, communication and computing.

In Europe, one of the most tangible initiatives is the experiment being conducted by Spanish energy company **Iberdrola**, which since 2024 has been testing a solution to optimise the location and management of large-scale storage systems for stabilising the electricity grid.

The test is carried out in cooperation with **Multiverse Computing**, a company specialising in quantum algorithms, and the **Gipuzkoa Quantum Program**, which aims to promote the implementation of quantum technologies in the Basque Country. Iberdrola implemented and tested Multiverse Computing's Singularity platform designed to manage quantum and quantum-inspired software. The project tested new methodologies for network optimisation in a region characterised by significant production of intermittent renewable energy, industrial and domestic consumption influenced by high temperature fluctuations, and the impact of the growth of the electric mobility charging network.

Iberdrola and Multiverse Computing announce pilot project success to optimise battery installation in the grid

The joint venture **Eniquantic** emerged from the collaboration between energy giant **ENI** and **ITQuanta**. ENI is already active in the High Performance Computing sector with one of the world's most powerful supercomputing machines (i.e. HPC6, included in the international Top 10 in 2025) to harness computing power for activities related to the energy transition, geodesy and the search for new hydrocarbon deposits, as well as advanced modelling of new materials and complex energy management networks. Eniquantic is working on the development of a full stack quantum machine (hardware and software).
Eniquantic will be able to exploit ENI's HPC6 supercomputer for testing and demonstrating hybrid quantum and traditional supercomputing activities. Looking ahead, ENI and ITQuanta have identified three use cases that are highly relevant to the energy sector: energy generation and storage, particularly in grids characterised by the presence of renewables; advanced simulation and modelling for nuclear fusion; and advanced analysis of complex systems, also for activities related to energy trading and those commodities that are part of the value chain.

Eni launches Eniquantic, a new venture for the technological development of quantum computing

Many energy transmission network operators say they are interested in working on quantum technology in the long term, exploring the possibilities offered by this all-round technology in varying degrees. In Italy, for example, grid operator **Terna** has adopted an approach to innovation called the 70 – 20 – 10 Model, where the last figure represents 10% of the innovation projects carried out on disruptive technologies including quantum computing, again with a view to identifying potential new solutions for grid optimisation.

Transport and logistics: NP-Hard problem solving

Transport is another very interesting area of application for quantum technologies, particularly due to the potential offered by quantum computing.
Transport and logistics are extremely complex to manage and plan in computational terms, given the very high number of variables to consider and the tight deadlines for data processing. In some cases, urban transport networks or supply chains require optimisation activities that may include many interdependent variables, often not directly related to the transport sector, but which nevertheless have a potential impact on it, such as weather-related data.

The ability of quantum computers to simultaneously process many combinations of different solutions will make it possible to manage *Non-deterministic Polynomial-time Hard (NP-Hard)* problems.
NP-Hard problems processed by traditional computers require calculation times that grow exponentially with the size of the problem being analysed, thus making exact resolution impractical in many cases.
Two typical examples of this category of problems are the *Travelling Salesman Problem* (TSP), whose objective is to identify the shortest route to visit all the nodes on the route at least once and then return to the starting point, and the *Vehicle Routing Problem* (VRP), used to assign optimal routes and paths to fleets of vehicles subject to restrictions such as time constraints.

As the number of these variables increases, the corresponding problems fall into the NP-hard category, posing a considerable challenge in terms of complexity of resolution.

Problems related to dynamic flow management have so far been addressed mainly by heuristic models or other optimisation algorithms. These models work very well in cases where variability is limited but are poorly scalable and unresponsive in the case of changing conditions. Therefore, quantum computing can provide a real solution to the limits of scalability and responsiveness, reducing processing times compared to HPC systems currently available.
In the transport and logistics sector, this translates, for example, into the possibility of considering meteorological phenomena and extraordinary events within the models with greater flexibility while guaranteeing better accuracy of results. This capability will be particularly relevant in the coming years when fleets of self-driving vehicles will move alongside human drivers on our infrastructure.

IBM proposes several use cases where quantum machines contribute to optimisation in the transport and logistics sector, from managing last-mile deliveries in a large city to sustainable routing in the maritime sector. The last-mile delivery use case involved a commercial vehicle operator in the New York City area. In that case, the system was designed to plan routes and deliveries, taking into account all the time, weather and urban constraints of the area in question. By introducing a quantum layer in the management of these deliveries, costs and time have been optimised, resulting in environmental, social and economic benefits.

Exploring quantum computing use cases for logistics

In France, **Pasqal** and **CMA CGM** initiated a Proof of Concept (PoC) in 2024 to demonstrate the potential of quantum computing applied to port logistics management, and in particular container handling, thus improving related supply chains. The PoC will exploit a dedicated quantum machine produced by Pasqal and installed in Marseille, with the aim of facilitating knowledge exchange between real users and quantum computer operators. The system will make it possible to optimise the management of loading, unloading and handling of containers according to parameters predefined by the companies, to reduce costs and environmental impact.

CMA CGM Group and Pasqal join forces to leverage quantum technologies for maritime transport and logistics

Quantum technologies can provide new ways to address what are now major challenges in the development of **self-** or **semi-driving vehicles**, first and foremost by increasing the safety of vehicle communications and navigation systems through quantum sensing.

Chapter 3 describes some of the major companies and start-ups that are working on next-generation quantum sensors and exploiting the extreme precision of these devices for navigation in all those contexts where satellite systems, such as GPS and Galileo, are not available. In particular, atomic clocks, accelerometers and quantum gyroscopes make quantum Positioning, Navigation and Timing (PNT) services possible with accuracies comparable to those achievable with satellite navigation.
These new sensors enable extremely high-performance forms of inertial navigation, which can be used both in dual-use and as a redundant safety system for self-driving vehicles. Dual-use applications, with potential for both civilian and security use, are driving the development of this niche market. In fact, the main aim is to provide hardware/software solutions that guarantee the continuity of positioning and navigation services under all operating conditions.

The US-based **Infleqtion** is working on the topic of quantum sensors for advanced inertial navigation with its Quantum Enhanced Inertial Navigation Systems (Q-NAV) project, funded by the UK Government through Innovate UK. The company is collaborating with the Royal Navy and other industrial partners to build an inertial navigation platform using quantum technologies. Tests with the Royal Navy under real-life conditions were carried out between 2024 and 2025, demonstrating the effectiveness of the solution.

Infleqtion

In the US, a grouping of companies, including **Lockheed Martin, Q-CTRL** and **AOSense**, is working on a quantum navigation system for those environments where satellite navigation systems are unavailable due to natural reasons or intentional interference. The system is designed to enable autonomous quantum navigation, Quantum-enabled Inertial Navigation System (Qu-INS), for drones and vehicles by exploiting a next-generation atomic interferometer (see Chapter 3). Therefore, such a system is immune to jamming and/or damage to satellite navigation signals, allowing the high-precision movement capability of the vehicles using it to be extended.

#video
Quantum Navigation: A New Way to Find Your Way

The evolution of this technological approach sees the self-driving of land vehicles and aircraft in the civil sector as the next likely area of expansion.
A series of tests in this regard was carried out in 2024 in the London Underground. The Imperial Centre for Cold Matter research group at **Imperial College London** has demonstrated the potential of a high-performance quantum accelerometer that enabled researchers to determine the position of the underground train on which it was mounted without the need for external signals. Applied to the network of an underground railway system, a system of this type would reduce the costs of implementing and managing the entire train location infrastructure. Therefore, there could be significant time and cost savings, both during the construction phase and in the management of the infrastructure.

'It's the perfect place': London Underground hosts tests for 'quantum compass' that could replace GPS

Despite the results achieved and promised by these technologies in the areas of smart grids and transport, companies and research centres still face significant challenges in using these tools on a large scale in real-world contexts. The most pressing challenges come from the miniaturisation of components and energy consumption, as well as the lack of standardisation of hardware and software interfaces.

A further emerging challenge concerns the integration of quantum technologies into existing infrastructures and commercial systems. This process requires ensuring backward compatibility with current standards, scalability of new solutions and interoperability between heterogeneous hardware and software components.

The very issue of integrating these technologies into existing products and infrastructure appears to be one of the most significant obstacles to the development of quantum technologies in the energy and transport sectors today.

4.3 Financial Services

The financial and insurance sectors are among the most exposed and, at the same time, among the most interested in the emergence of quantum technologies. These can be used to analyse and process enormous volumes of data in extremely short times, almost in real time, to support critical decisions in trading, risk management or financial asset allocation. Furthermore, they can be used to implement advanced security tools to protect communications and transactions. The investments made by large banking and insurance groups in quantum are therefore both a response to a strategic challenge and a means of strengthening the sector's competitiveness in the medium to long term.

According to an analysis by McKinsey, the most relevant applications will be:

- Optimisation of financial portfolios
- Rapid and advanced simulations of risk indicators and asset pricing
- Fraud detection and anti-money laundering activities
- Credit scoring and calculation of the insolvency probability
- Optimisation of operations and back office

Research published by Evident in 2025 highlights the banking sector's interest in quantum technologies, with 80% of the 50 banking groups analysed either having activities in this field in place or having expressed an intention to initiate them. Quantum technologies related to communications are considered important for secure financial transactions and communications, while quantum computing, in addition to cybersecurity, is considered useful for solving various types of problems, including optimisation and fraud detection.

Risk management and information protection

The report sees US bank JP Morgan Chase as a trailblazer in the adoption of quantum technologies. The British bank HSBC and the Italian bank Intesa Sanpaolo are listed as strong runners-up.

Special Edition | Banks' Quantum Solace

One of the practical reasons that is driving many institutions in the financial and insurance sector to implement secure solutions based on quantum communication, and QKD in particular, is the fear of **Harvest Now, Decrypt Later (HNDL) attacks.** This type of attack is based on the possibility of intercepting and storing sensitive information today and then decrypting it in the future, when the computing power needed to execute Shor's algorithm is available (see Chapter 1).

In order to prevent this type of attack, it becomes necessary to encrypt communications and databases containing sensitive information with the most future-proof technologies available, such as QKD, from the outset, since much of the data considered critical today will retain their relevance, fully or nearly so, for the foreseeable future. The financial sector is particularly exposed to HNDL attacks due to the amount of transactions it handles on a daily basis and the need to store some data for very long periods of time, up to 10 years.

Toshiba is one of the most active players in the implementation of QKD applications for the financial world, with partnerships with large banking groups such as HSBC (how QKD works was discussed in Chapter 3). Toshiba's QKD system is designed to be easily integrated into existing IT infrastructures, adding a layer of protection. This approach is being taken by many players in the industry, both large companies and start-ups.

In addition to QKD, solutions employing technologies considered quantum-safe such as **Post-Quantum Cryptography (PQC)** algorithms are increasingly being implemented.

In 1995, the article by Peter W. Shor "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer" showed that an appropriate algorithm, harnessing the computing power of a quantum computer, would be able to violate the standard public-key cryptography protocols commonly used at the time, once it became available.
Today, thirty years later, they still constitute a security standard adopted in a significant proportion of secure communications transiting computer networks, making Shor's demonstration highly topical. The same calculation required to break the RSA cryptosystem would take an enormous amount of time (trillions of years) with a classical high-performance computing system, but only a few hours with a sufficiently coherent and stable quantum computer.

PQCs do not directly use quantum technologies from a physical point of view, but are classical algorithms that can be run on conventional computers, which nevertheless can withstand quantum attacks. Many companies and start-ups are working on PQC techniques; however, few are focusing on implementing this technology in a highly regulated field such as finance.

CryptoNext Security is a French start-up that has developed a set of tools to add a layer of protection to data and its transmission in a quantum-safe perspective. The company implemented a modular platform that analyses existing communication systems and integrates with them. CryptoNext Security offers a system based on a gradual transition from classical cryptography to PQC. This progressive approach is designed for all those highly regulated areas, such as banking or insurance, where every element has to be checked very carefully. The start-up already works with major European banking and industrial groups.

CryptoNext Security

PQShield is an Oxford University spinoff specialising in implementing hardware and software solutions in the PQC area. The deep tech nature of the start-up made it possible for it to participate in international standard-setting tables related to post-quantum security (NIST, ESTSI, ISO). PQShield offers hybrid and scalable solutions designed for all sectors where communication security is considered critical. Among the use cases that the company is developing, in addition to the more traditional ones, there are some that provide insight into how PQC technology can be applied in multiple areas, such as Industrial Internet of Things (IoT) and Identity and Paymentech.

PQShield

04 / Industry Applications

A similar approach is proposed by **pQCee**, focusing on post-quantum cybersecurity. The Singapore-based company concentrates on all those data-intensive areas that need PQC. pQCee works in particular on systems that are compatible with the standards already in place today, especially in highly regulated industries. One of the first use cases handled by the company concerns the protection of the authenticity and integrity of data related to financial transactions. pQCee plays a leading role in the deployment of PQC technologies in institutions and companies in South East Asia, where many potentially privacy and security-impacting activities are performed on mobile devices and with inadequate protection.

pQCee

In particular, the **financial risk** indicators that can be most accurately and quickly calculated by a quantum computer include Value at Risk (VaR) and Conditional Value at Risk (CVaR) expected average losses. These metrics are complex to calculate due to the large number of variables present.

4.4 Final Considerations

Quantum technologies are becoming established in various sectors as enhancements to existing technologies, while in other areas they will have such a profound impact that they will redefine the way we think about high-performance computing and communications security and how we measure the infinitely small.

Quantum sensing will continue on its way towards miniaturisation and certification of components and machinery. A likely development will see the emergence of wearable and clinically validated devices. The timing of this revolution in sensor technology is currently impossible to determine.

Quantum communication is attracting interest from large industrial groups, research centres and start-ups due to its enormous commercial potential, both in the civil and dual-use sectors. This family of technologies responds effectively and concretely to a range of requests made by institutions, telecommunications groups, commercial entities, companies and military organisations, all of which have a growing need to guarantee the solidity of communication networks and the security of transmitted information.

In quantum computing, fault-tolerant systems are expected to be developed, with the ability to perform calculations below a certain error threshold, making them usable from around 2030 onwards. The transition, expected to take place over the next 5 to 10 years, is unlikely to be linear. However, there is absolutely no clarity as to which technology or group of technologies will become the standard. Many companies are trying to reduce this uncertainty by working on modular, hybrid platforms that can adapt to different types of quantum machines and integrate with traditional HPC systems. The same uncertainty about the dominant standard also emerges on the software and algorithmic side. From this perspective too, the path towards hybrid and adaptable platforms seems to be a solid response to existing challenges.

Perhaps the most systemically relevant issue in the next 5 years, regardless of quantum technology, will be that of **quantum sovereignty**: control over technology development and the supply chain to implement it will become increasingly strategic. Controlling the ecosystem will be a crucial point in securing the competitive advantage that quantum technologies promise, especially with regard to quantum computing.

About Intesa Sanpaolo Innovation Center

Intesa Sanpaolo Innovation Center is the Gruppo Intesa Sanpaolo company dedicated to frontier innovation. It explores future trends and scenarios, develops multidisciplinary applied research projects, supports startups, accelerates business transformation for companies according to the criteria of Open Innovation and the Circular Economy, facilitates the development of innovative ecosystems and disseminates innovation culture, in order to make Intesa Sanpaolo the driving force behind a better informed, inclusive and sustainable economy.
The Innovation Center, with its headquarters on the 31st floor of the Intesa Sanpaolo skyscraper and its national and international network of hubs and laboratories, is a relationship facilitator for the other stakeholders of the innovation ecosystem – such as businesses, startups, incubators, research centers, universities, national and international institutions – and a promoter of new forms of entrepreneurship and their access to risk capital, with the support of venture capital funds, thanks also to the Neva SGR subsidiary.

About LINKS Foundation

Leading Innovation and Knowledge for Society is a private research and innovation organisation founded by Politecnico di Torino and Fondazione Compagnia di San Paolo. It contributes to a development process based on the principles of social cohesion and sustainability, with the aim of fostering progress in scientific and technological research as well as the cultural and professional growth of society. The founding values guiding LINKS' work are the production, attraction, preservation, critical elaboration, and transfer of knowledge in the fields of engineering, architecture, and other polytechnic sciences, also through technology transfer activities and services supporting the local ecosystem. The Foundation pursues goals of social utility, promoting the civil, cultural, and economic development of the contexts in which it operates. LINKS acts as a platform for transferring knowledge from academia, research centres, and scientific literature towards industry, public administration, cultural institutions and third-sector organisations. Its role is to support the maturation of technologies and innovative solutions, achieving impact through the work of researchers with strong technical and scientific expertise.

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