Politecnico di Torino

Master's Degree in Engineering and Management

A.Y. 2024/2025

Graduation session November/December 2025

Quantum computing for competitive advantage: a strategic framework for industrial adoption in Europe

Supervisor:

Prof. Marco Cantamessa

Co-supervisor:

Matteo Vannucchi

Candidate:

Federica Ciancetta

Summary

Introduction

One of the most exciting technological developments of the twenty-first century, quantum computing has transformed over the last ten years from a primarily theoretical research area. Quantum computers promise to execute some computations exponentially faster than classical machines by utilizing the concepts of superposition, entanglement and interference found in quantum mechanics. Quantum technologies are positioned as revolutionary general-purpose technologies that have the potential to revolutionize sectors like chemistry, logistics, finance, energy and materials science due to their capacity to speed up simulation, optimization and learning tasks. But the path from scientific study to commercial application is still convoluted, uncertain, and lengthy. The high complexity, expensive infrastructures, protracted development timelines, and ecosystem interdependencies of quantum computing set it apart from earlier digital technologies. Consequently, businesses and policymakers are faced with a strategic challenge: how and when to use quantum technologies to increase competitiveness while lowering risk.

In order to answer that question, this thesis looks at the industrial adoption of quantum computing from a managerial and strategic standpoint, paying special attention to the European context. By offering a thorough framework that helps businesses navigate the different phases of quantum engagement, from exploration and experimentation to integration and ecosystem leadership, the goal is to close the current gap between technological maturity and organizational readiness.

The Quantum Adoption Pathway (QAP), an original and atemporal framework created by the author, is the main contribution of this work. The QAP converts knowledge from well-established theories of innovation and adoption into a workable, fact-based roadmap that is especially suited to the circumstances of quantum technologies. It helps managers and policymakers make well-informed, risk-aware decisions about quantum engagement by coordinating organizational capabilities, technical advancements, and strategic intent.

Despite extensive technical and scientific discussion, little is known about quantum computing's organizational and managerial aspects. Current adoption models, including the Dynamic Capabilities perspective, the Technology Readiness Level (TRL) framework, the Technology Acceptance Model (TAM), and Rogers' Diffusion of Innovations, provide useful conceptual tools but fall short in encapsulating the complexity of the quantum domain. Quantum technologies continue to face challenges with limited trialability and uncertain commercial value, despite Rogers' model explaining how innovations spread based on visibility and perceived benefit. Technical advancement is efficiently measured by TRL scales, but organizational and ecosystem elements that are crucial for practical adoption are overlooked. The collective and strategic decision-making that characterizes industrial settings cannot be captured by TAM, which was initially developed for consumer or software innovations. Although the dynamic capabilities framework acknowledges the necessity of transformation and sensing, it does not provide operational guidance for gauging readiness. As a result, businesses lack a logical approach to align technical advancement, capacity building and market timing. The primary driving force behind this research is this theoretical and practical gap.

In contrast, the development of quantum computing involves long investment cycles, hybrid infrastructures, and uncertain hardware roadmaps. Adoption of quantum computing is contingent upon ecosystem maturity, access models, and policy support in addition to technical viability. Because of these circumstances, a multifaceted adoption framework that connects technological advancement to organizational change and strategic alignment must be created.

Thus, the study aims to achieve two main goals: first, to assess the current level of quantum readiness in terms of technology, organizations, and policies, with an emphasis on the European context, and second, to create a thorough adoption model that helps businesses to go from awareness to integration in a methodical manner backed by quantifiable competencies. The study is guided by four research questions: How can organizational and technological preparedness be evaluated together? Which industries present the most promising avenues for early adoption? What strategic and managerial approaches can help create an evidence-based, long-term integration path? In what ways can European coordination and public policy hasten the shift from high-quality research to industrial competitiveness?

The thesis integrates managerial design, policy analysis, and theoretical synthesis to address these issues. It combines an empirical examination of European policies, infrastructures, and national initiatives with a thorough literature review on quantum technologies and adoption theories. A global standard for assessing Europe's position in the quantum race is provided by comparative analysis between the US and China.

Furthermore, sectoral analyses show how absorptive capacity and innovation capability determine adoption readiness as they look at the application potential of quantum computing in five major industries: manufacturing, energy, logistics, healthcare and chemistry, and finance. Lastly, the study presents the Quantum Adoption Pathway, a managerial tool called the QAP transforms the unclear idea of readiness into specific operational steps, each with its own objectives, duties, and gate requirements.

There are four major chapters in the thesis: the scientific and technological underpinnings of quantum computing are laid out in Chapter 1, which also describes the key hardware platforms, algorithmic paradigms and maturity indicators like the TRL and Q-TRL scales. It introduces the concept of quantum advantage and explores how technological readiness affects strategic decision-making.

The European quantum scene is examined in Chapter 2 in light of international competition. It examines national and regional initiatives, public investments and the expanding network of industrial players, startups, and research centres throughout the continent. While highlighting Europe's scientific prowess, well-coordinated governance, and moral approach to technology, the chapter also highlights structural issues like fragmentation, a lack of private capital mobilization and reliance on non-European supply chains.

In Chapter 3, the potential effects of quantum computing on various industries are evaluated through an emphasis on industrial applications and use cases. It draws attention to domains like optimization, simulation, and machine learning where hybrid quantum classical solutions may yield real benefits through the prisms of absorptive capacity and innovation capability. The analysis emphasizes that the ability of European industries to incorporate quantum capabilities into current digital transformation processes will be just as important to their competitiveness as technological advancement.

The strategic framework for industrial adoption is finally presented in Chapter 4, which also introduces the Quantum Adoption Pathway and the associated competency architecture. Five progressive phases are defined by the framework: exploration, proof of concept, integration, scaling, and leadership and ecosystem shaping. Each phase is backed by particular deliverables, competencies and gate criteria that guarantee preparedness before moving forward. It provides a useful road map that companies can utilize to build internal capabilities, match strategic goals with quantum initiatives and interact with the wider ecosystem in an efficient manner.

The primary theoretical and practical contribution of the thesis is the Quantum Adoption Pathway. By combining organizational, technical, and policy aspects into a single framework, it assists businesses in navigating uncertainty through evidence-based development. The competency architecture, which supports the framework, outlines the abilities, responsibilities, and artifacts needed at every level, from platform engineering and ecosystem leadership to early sensemaking and algorithmic experimentation. The framework ensures that resources are invested effectively by allowing organizations to make adoption decisions based on evidence rather than hype by connecting measurable competencies to decision gates.

From a managerial perspective, businesses looking to use quantum technologies responsibly can use the QAP as a indicative and decision-support tool. It assists executives in finding the best entry points, allocating resources effectively and developing internal knowledge in step with technological advancements.

This study has two ramifications. In the near future, the framework helps organizations create hybrid workforce training programs, readiness assessments and pilot evaluation metrics. In the long run, it helps Europe achieve its goal of becoming a leader in responsible quantum innovation by encouraging collaboration between policy, industry and academia.

However, the research admits that the quantum field is changing quickly. Due to the constant changes in hardware performance, software stacks, and benchmarking standards, the Quantum Adoption Pathway needs to be adjusted on a regular basis to stay up to date with the latest advancements.

Future studies should look into the model's longitudinal validation, how firms move through the suggested phases, which competencies are most indicative of successful integration, and how policy tools can lower adoption barriers, especially for small and medium-sized businesses.

In summary, this thesis aims to address a central query: how can quantum computing progress from a promising scientific concept to an industrial reality? It gives businesses a structured but adaptable way to interact with quantum technologies in a methodical and strategic way by fusing technological knowledge, ecosystem mapping, and managerial design. In order to facilitate Europe's transition to a competitive, sustainable, and independent quantum future, the proposed Quantum Adoption Pathway links scientific advancement with commercial value.

Chapter 1 Fundamentals of quantum computing

1.1 Quantum computing: principles and core concepts

Quantum computing diverges from the predictable logic of classical systems and embraces the uncertain, non-local properties of quantum mechanics. The idea was first suggested in 1982 by Feynman (Feynman, 1982) and formalised in 1985 by Deutsch (Deutsch, 1985). Quantum computing concept comes from the realisation that some physical systems can't be effectively simulated using classical methods. As the field has developed, it has shifted from a theoretical idea to a cutting-edge technology, with increasing effects on computing, optimisation and simulation tasks (Anumolu, 2025).

1.1.1. Qubit and superposition

The fundamental idea of quantum computing theory that sets it apart from classical computing is the quantum bit, or qubit. While the classic can exist in one or two discrete states (0 or 1), computing can exist in a superposition of two states. More correctly, the state of an individual qubit is given by:

$$|\psi\rangle = \alpha \mid 0 \rangle + \beta \mid 1 \rangle, \tag{1}$$

Where α e β are complex probability amplitudes such that $|\alpha|^2 + |\beta|^2 = 1$.[1]
The type of parallelism that increases exponentially with the number of qubits is made possible by this property, which enables quantum systems to encode and manipulate a computational basis of states using only n qubits. (Anumolu, 2025) (Balamurugan K. S., Sivakami, Mathankumar, Yalla Jnan Devi Satya, & Irfan, 2024).
A large portion of the excitement surrounding the potential benefits of quantum computing is based on the fact that the quantum system with n qubits can represent all 2^n configurations at once, a classical system with n bits can only represent one configuration at a time. This capability does not imply that quantum computers perform calculations in parallel, but they employ unitary operations to control quantum

[1] α and β are complex-valued probability amplitudes rather than simple probabilities in quantum mechanics. The probabilities of observing the qubit in states $|0\rangle$ and $|1\rangle$ are indicated by the squared moduli, $|\alpha|^2$ and $|\beta|^2$, respectively. There is no classical counterpart to the interference effects that quantum states exhibit due to their capacity to assume complex values.

states and utilise interference to squelch erroneous pathways and steer computation in the right direction. (Meng-Leong & Sin-Mei, 2023).

It is easier to think of a classical bit as comparable to a coin that is flat on a table and shows either heads or tails. Instead, a qubit is similar to a coin that is spinning in midair, it is not just heads or tails, but a mix of both, until it is observed. The qubit does not "collapse" into a definitive state until the measurement occurs, much like a coin that is spinning and lands on one face (Natalucci, 2025).

1.1.2. Entanglement and correlation

A second principle of quantum computing is entanglement, a non-classical correlation that occurs when the state of one qubit depends on the state of another. A Bell state, which is a maximally entangled state of two qubits, is defined as follows:

$$|\phi+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \quad (2)$$

demonstrating that the measurement of one qubit instantly determines the state of the other, independent of spatial separation. Multi-qubit gates, teleportation protocols and quantum error correction all depend on entanglement.

Two gloves stored in separate boxes are a common illustration. Before anyone opens it, everyone can deduce that the left-hand glove is in the other box if it is known that the right-hand glove is in the first one. This is simply a correlation in the classical realm, where the gloves had distinct identities from the outset. In the quantum realm, the gloves are connected: one remains neither left nor right until the other is observed, and measuring one instantaneously determines the state of the other (Natalucci, 2025).

1.1.3. Interference

Quantum interference, the third fundamental principle, allows probability amplitudes to combine constructively and destructively. It is essential to quantum algorithms like Grover's algorithm[2] (see figure 1), which increases the likelihood of correct answers through interference. This means that even in the presence of noise and decoherence,

[2] One of the fundamental quantum search algorithms, Grover's algorithm provides a quadratic speedup over traditional brute-force techniques. Grover's method amplifies the probability of the correct result through constructive interference, finding the desired element in approximately $\sqrt{N}$ steps, whereas a classical search through N possibilities requires an average of N/2 evaluations. It shows how interference can be used for computational advantage, even though it isn't exponentially faster.

well-designed quantum circuits can enhance the probability of a successful outcome through controlled evolution and measurement (Anumolu, 2025). Unlike classical statistical noise, this principle allows certain amplitudes to cancel each other out while others reinforce, much like waves on a pond. In quantum circuits, this behaviour is connected algorithmically to guide computations toward desirable outcomes. It enables more effective convergence of solutions by providing algorithmic control over computational trajectories in Hilbert space[3], By giving algorithmic control over computational trajectories in Hilbert space, it facilitates more efficient convergence of solutions. The Bloch sphere representation will be used to further illustrate this idea in the section that follows. Imagine ripples on a pond created by two stones thrown close together. Where the ripples meet, the waves either amplify or cancel out. Quantum systems behave similarly, but with probability amplitudes instead of water waves.

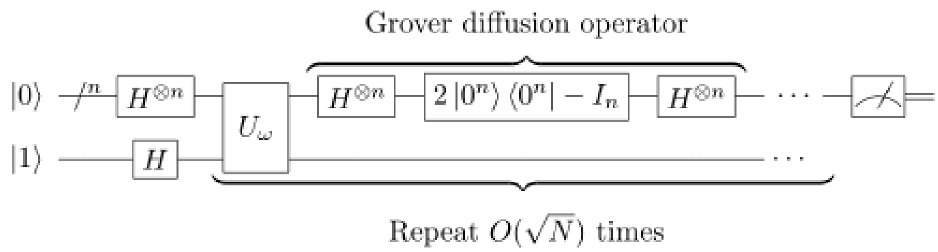

Figure 1.1.: Grover's algorithm (Bender2014, s.d.)

Interference, entanglement and superposition combine to create a new class of quantum algorithms that may perform better than their classical counterparts. Regardless of these developments, existing hardware constraints continue to impede the realisation of useful quantum computing. Gate fidelities, coherence times and qubit counts are still insufficient for complete fault-tolerant computing in the Noisy Intermediate-Scale Quantum (NISQ) regime[4], which is where the majority of current platforms operate (Preskill J. , 2018).

[3] The Hilbert space is an abstract mathematical space used in quantum mechanics to represent every possible state of a quantum system. In this space, a vector represents each quantum state, and rotations or transformations of these vectors represent quantum operations. Therefore, controlling trajectories in Hilbert space entails using precisely planned unitary operations to direct a quantum state's evolution toward a desired result.

[4] John Preskill coined the term "Noisy Intermediate-Scale Quantum" (NISQ) in 2018 to describe the new generation of quantum devices with tens to several hundred qubits. Although these systems are capable of handling complex calculations, they are still constrained by noise, short coherence times, and the lack of complete error correction.

1.1.4. Hilbert space and the Bloch sphere representation

Theoretically, quantum computing works in the formalism of Hilbert space, a complex vector space in which unitary transformations correspond to operations, and each quantum state is a vector. For single-qubit dynamics, visual representations like the Bloch sphere offer intuitive comprehension (see figure 2), with rotations corresponding to quantum gates like Pauli-X, Y, Z and Hadamard operations (Balamurugan K. S., Sivakami, Mathankumar, Satya Prasad, & Ahmad, 2024).

The Bloch sphere is one of the most fundamental tools for visualizing and understanding the state of a single qubit. It provides a geometric representation of pure qubit states in a three-dimensional unit sphere, offering intuitive insight into superposition, relative phase and unitary transformations (Nielsen & Chuang, 2010) (Preskill J. , 1998).

Mathematically, the general state of a single qubit can be written as:

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle \tag{3}$$

where $\theta \in [0, \pi]$ and $\phi \in [0, 2\pi]$ define the polar and azimuthal angles on the Bloch sphere. Each pure state thus corresponds to a point on the surface of the sphere, while mixed states are represented as points within the sphere.

The Bloch sphere is particularly effective in visualising quantum gate operations. Pauli-X, Y, and Z gates correspond to rotations about the respective axes, while the Hadamard gate represents a rotation that maps basis states to superposition states. In this geometric framework, all single-qubit unitary operations are equivalent to three-dimensional rotations, simplifying the understanding of qubit manipulation.

The north and south poles of the Bloch sphere represent the computational basis states and $|0]$ $|1]$, respectively.

The equator ($\theta = \frac{\pi}{2}$) contains all equal superpositions of $|0]$ and $|1]$, with the phase ϕ determining the orientation. For instance, $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ lies on the x-axis, while $|i\rangle = (|0\rangle + i|1\rangle)/\sqrt{2}$ it lies on the y-axis (Nielsen & Chuang, 2010).

Although strictly applicable to pure states of single qubits, the Bloch sphere provides essential intuition that extends to more complex systems. Advanced formulations, such as the two-sphere entanglement model (Wie, 2020) or the Bloch matrix framework (Gamel, 2016) attempt to generalise the concept to multi-qubit and entangled states. In the context of quantum computing, the Bloch sphere is instrumental in educational settings and early-stage quantum circuit development. It visually illustrates how decoherence acts as a contraction toward the centre of the sphere, and how measurement corresponds to projection onto the z-axis. This makes it not only a geometric model but also a conceptual bridge between Hilbert space formalism and the physical operation of quantum systems.

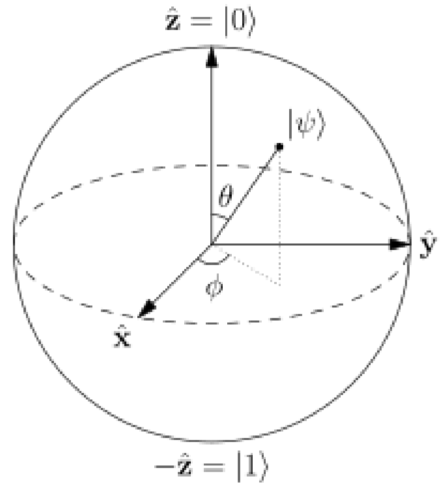

Figure 1.2.: Representation of the Bloch Sphere (N.d., ResearchGate, s.d.)

1.2. Quantum hardware technologies

Even though quantum computing has great potential, the abstract qubit model cannot be realized without extremely complex physical devices. One of the biggest engineering problems of the twenty-first century is the construction, manipulation and scaling of quantum bits. Qubits need platforms that can support sensitive quantum phenomena like superposition and entanglement and shield them from decoherence, in contrast to classical bits that can be encoded in silicon-based transistors. Over the past 20 years, several hardware strategies have been developed, each with a unique set of trade-offs between technological maturity, scalability, gate integrity and coherence time. Another significant challenge is the inherent vulnerability of qubits, rendering them quite susceptible to errors. The success of noise reduction and quantum error correction will crucially influence not only which hardware platforms succeed, but also when and how quantum advantage can feasibly be attained.

1.2.1. Superconducting qubit

Superconducting qubits are one of the leading platforms for building scalable quantum computers. They are applied using superconducting circuits based on Josephson junctions' nonlinear elements that can exhibit quantised energy levels. Their fabrication leverages mature microelectronics processes, enabling integration into larger, more complex systems (Huang, Wu, Fan, & Zhu, 2020).

Superconducting qubit systems are categorised according to the degree of freedom used for encoding quantum states: charge, flux, and phase. Each qubit type reflects a different balance between the charging energy E_C, Josephson energy E_J and inductive energy E_L. While charge qubits exploit the quantisation of excess Cooper pairs on a superconducting island[5], flux qubits encode information in persistent current states through superconducting loops. Phase qubits use the phase difference across the junction as the operational degree of freedom.

A key innovation was the introduction of the transmon qubit (see figure 3), which emerged as a charge qubit operating in the regime $\frac{E_J}{E_C} \gg 1$. This suppresses sensitivity to charge noise at the cost of reduced anharmonicity, making it more robust against decoherence while retaining addressability.

The transmon[6] has been widely adopted in circuit quantum electrodynamics (circuit-QED) architectures due to its favourable coherence properties and ease of integration. Enhancements such as the Xmon qubit with planar geometry and improved control connectivity and the 3D transmon, which reduces dielectric losses via a 3D cavity, exemplify refinements in engineering to improve fidelity and isolation (Koch, et al., 2007) (Barends, R., & J., 2014).

Recent alternative designs include the fluxonium qubit, which uses a large inductance to reduce flux noise, and the 0–π qubit, which leverages circuit symmetry to suppress

[5] Cooper pairs are bound electron pairs that flow through a superconductor together without encountering any electrical resistance. Their collective behaviour underlies superconductivity and enables quantum effects such as tunnelling in Josephson junctions.

[6] The charge qubit design gave rise to the transmon, a kind of superconducting qubit that functions in a regime where the Josephson energy is significantly higher than the charging energy. Coherence and stability are enhanced by this arrangement, which lessens sensitivity to charge noise.

both charge and flux noise channels. These architectures aim to push coherence times beyond 0.5 milliseconds and to enable fault-tolerant thresholds through topologically protected modes (Huang, Wu, Fan, & Zhu, 2020).

Despite significant progress, decoherence is still driven by dielectric loss, quasiparticle poisoning and magnetic flux instability. Moreover, large-scale integration is hindered by the complexity of routing control lines at cryogenic temperatures, the need for frequency crowding mitigation and the nontrivial task of implementing two-qubit gates with both high fidelity and low crosstalk.

From a systems perspective, superconducting qubits have served as a backbone for demonstrating key building blocks of quantum computation: single and two-qubit gate operations, readout mechanisms via dispersive coupling and early implementations of surface code logic and error correction.

They continue to represent a central platform in both commercial roadmaps and academic exploration of quantum hardware maturity.

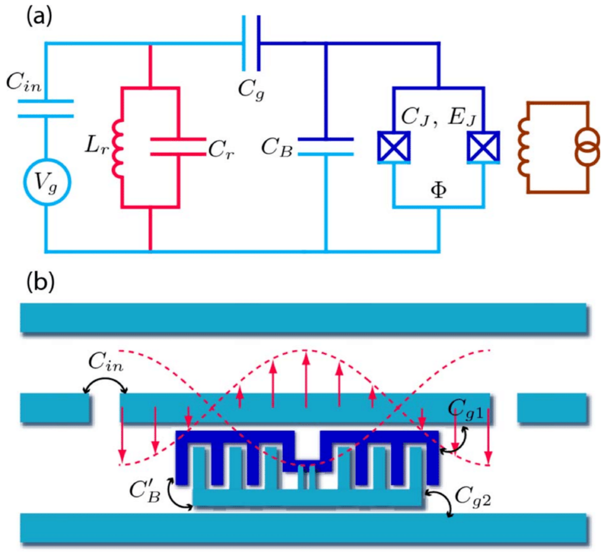

Figure 1.3.: Schematic of a Transmon qubit and its effective circuits *(N.d., ResearchGate, s.d.)*

1.2.2. Trapped Ion Qubit

Trapped ion qubits represent one of the most mature and high-fidelity platforms for quantum information processing. In this architecture, individual ions, typically alkaline-earth or alkali-metal ions, are confined in electromagnetic traps and manipulated using laser or microwave radiation. Each qubit is encoded in two stable internal states of a single ion, often hyperfine or optical clock states, which offer long coherence times on the order of seconds or more (Monroe & Kim, 2013).

The ions are confined in either linear Paul traps or Penning traps[7], where electric or magnetic fields create a potential well that spatially isolates the ions into a Coulomb crystal. High-precision laser beams are used to initialise, manipulate and read out the qubit states. Quantum logic gates are implemented by exploiting collective motional modes of the ion chain, where entangling operations are achieved through spin-dependent forces applied via stimulated Raman transitions or Molmer–Sørensen schemes[8] (Leibfried, Blatt, Monroe, & Wineland, 2003).

Trapped ion systems exhibit exceptional gate fidelities, with single-qubit gate errors routinely below and two-qubit gate fidelities surpassing 99.5% in laboratory settings. One key advantage of ion-trap systems is their high degree of qubit uniformity and long-range Coulomb-mediated connectivity[9], enabling all-to-all gate schemes within small ion registers. This contrasts with nearest-neighbour coupling constraints in many solid-state platforms.

However, scaling up trapped ion systems presents notable challenges. As the number of ions increases, motional mode spectra become more complex and control crosstalk rises. To address this, modular architectures such as the Quantum Charge-Coupled Device (QCCD)[10] have been proposed, in which ions are shuttled between zones for gate operations, cooling and storage. Additionally, photonic interconnects and entanglement swapping protocols have been developed to link distant ion modules, supporting network-based scaling approaches (Brown, Kim, & Monroe, 2016).

1.2.3. Photonic Qubit

Photonic qubits encode quantum information into individual photons, typically using their polarisation, path, time-bin, or orbital angular momentum degrees of freedom. This approach to quantum computing offers several intrinsic advantages: photons interact weakly with their environment, are naturally mobile and can propagate

---

[7] Linear Electromagnetic devices called Paul and Penning traps are used to keep charged particles in space. While Penning traps use a combination of static magnetic and electric fields to achieve confinement, Paul traps use oscillating electric fields to dynamically stabilize ions.

[8] Quantum logic gates in trapped-ion systems communicate via the ions' common vibrational (motional) modes. In order to achieve entanglement, laser-driven, spin-dependent forces that couple internal spin states with collective motion are applied. These forces are typically implemented through stimulated Raman transitions or the Mølmer–Sørensen interaction.

[9] The interaction between charged ions via electrostatic (Coulomb) forces, which couple their motion and enable the sharing or transfer of quantum information between qubits, is known as Coulomb-mediated connectivity.

[10] Ions are physically moved between various trap zones for storage, cooling, and computation in the Quantum Charge-Coupled Device (QCCD) architecture for trapped-ion quantum computers. This modular design lowers qubit interference and increases scalability.

through optical fibres or integrated waveguides with minimal loss, making them particularly attractive for both quantum communication and distributed quantum processing (Jeremy, O'Brien, Furusawa, & Vučković, 2009).

In photonic quantum computing, qubit manipulation is achieved through linear optical elements such as beam splitters, phase shifters and polarising filters, together with single-photon sources and detectors. Since photons do not interact directly, entangling operations rely on measurement-induced nonlinearity, most notably via the Knill–Laflamme–Milburn (KLM)[11] protocol, which probabilistically implements two-qubit gates through ancillary photons and projective measurements (Knill, Laflamme, & Milburn, 2001).

There are two main approaches in photonic systems: discrete-variable (DV) encodings, which treat single photons as qubits and continuous-variable (CV) encodings, which manipulate quantum states of light described by field quadratures. DV systems are more compatible with quantum error correction schemes, while CV systems can leverage deterministic Gaussian operations and have shown promise in resource-efficient architectures (Braunstein & van Loock).

Recent advancements have been driven by integrated photonics platforms, which enable the fabrication of reconfigurable, low-loss quantum circuits on silicon or lithium niobate chips. These platforms support scalable architectures by combining photon sources, interferometers, and detectors on a single chip. Systems such as Borealis (Xanadu) and Jiuzhang (USTC) have demonstrated Gaussian Boson Sampling tasks[12] beyond classical capabilities, marking significant experimental progress (Zhong, et al., 2020) (Arrazola, et al., 2021).

Photonic qubit platforms face several challenges: high-efficiency, on-demand single-photon sources are still under active development, as is photon-number-resolving detection. Furthermore, scaling up requires synchronising many indistinguishable photons and implementing feed-forward control at high speed, which remains technologically demanding. Loss and probabilistic gates also hinder the implementation of fault-tolerant quantum computing.

[11] The KLM protocol, which relies on measurement-induced effects rather than direct photon–photon interactions, shows that universal quantum computation is achievable with only linear optical elements, single-photon sources, and detectors.

[12] In the computational task known as Gaussian Boson Sampling (GBS), photons traveling through a system of beam splitters and phase shifters create output patterns that are very challenging for traditional computers to replicate. Large-scale GBS was shown in the Borealis (Xanadu, Canada) and Jiuzhang (USTC, China) experiments, demonstrating the quantum computational advantage of photonic systems.

Nonetheless, photonic systems are uniquely suited for specific applications such as quantum key distribution, quantum repeaters and sampling-based quantum advantage demonstrations. Moreover, modular architectures based on photonic interconnects are expected to play a vital role in future quantum networks and hybrid systems.

1.2.4. Neutral Atom

Neutral atom qubits use ultracold atoms, typically alkali atoms such as rubidium (Rb) or cesium (Cs), as carriers of quantum information. These atoms are trapped in optical tweezers formed by highly focused laser beams, which can arrange them into one-, two- or three-dimensional arrays. The quantum states are encoded in the hyperfine ground states of each atom, offering long coherence times due to weak coupling with the environment (Saffman, Walker, & Molmer, 2010).

A key advantage of neutral atom platforms is their scalability. Optical trapping allows the generation of large, reconfigurable qubit arrays with hundreds of atoms at micrometre spacing. Qubit initialisation, manipulation and readout are achieved using laser-driven Raman or microwave transitions. Optical addressing systems enable specific gate operations, while global control pulses facilitate parallelism.

Entangling gates between atoms are implemented using the Rydberg blockade mechanism. When an atom is excited to a high-lying Rydberg state, its strong dipole-dipole interaction shifts the energy levels of nearby atoms, preventing their simultaneous excitation. This enables fast and controllable two-qubit gates over several microns of distance, with experimental fidelities approaching 97% (Levine, et al., 2019).

Neutral atom systems benefit from their intrinsic uniformity, as all atoms of a given species are identical, reducing calibration overhead. The technology also supports natural qubit transport via optical tweezers, allowing atom rearrangement to optimise gate patterns. Furthermore, recent demonstrations have shown Greenberger-Horne-Zeilinger (GHZ) entangled states involving over 20 atoms, indicating the potential for multi-qubit entanglement at scale (Bluvstein, et al., 2022).

However, several challenges remain, for example, achieving high gate fidelities requires suppression of technical noise, motional heating and laser phase fluctuations. Photon scattering and atom loss impose constraints on coherence and gate depth. Moreover, current architectures are mostly limited to two-dimensional qubit layouts and the integration of error correction remains at a prototypical stage.

In conclusion, these platforms are particularly suited for simulating spin models, solving optimisation problems, and exploring quantum many-body physics.

1.2.5. Spin Qubit

Spin qubits leverage the quantum spin states of individual electrons or nuclei confined in semiconductor nanostructures, such as quantum dots or donor atoms in silicon. These kinds of technologies encode quantum information in the two-level system formed by the spin-up and spin-down states of a single particle, offering a conceptually simple yet physically rich foundation for quantum computing (Loss & DiVincenzo, 1998).

Typically, electron spins are confined in quantum dots created by gate-defined electrostatic potentials within silicon or silicon–germanium heterostructures. The spin states are initialised and manipulated using microwave magnetic or electric fields, often through electron spin resonance (ESR) or electric dipole spin resonance (EDSR). Single-qubit gate fidelities above 99.9% have been demonstrated and coherence times can reach milliseconds in isotopically purified silicon environments (Veldhorst, et al., 2014).

Two-qubit gates are implemented by coupling adjacent spins via exchange interactions, which are highly tunable but require precise control of inter-dot tunnel coupling. Recent work has also explored long-range coupling via superconducting resonators or quantum buses, aiming to overcome the layout constraints of nearest-neighbour architectures.

One of the most compelling advantages of spin qubits lies in their compatibility with standard CMOS fabrication processes. This raises the prospect of integrating quantum processors with classical control electronics on the same chip, enabling dense qubit arrays with high scalability potential. Moreover, the physical footprint of a spin qubit is among the smallest of all hardware platforms, allowing the possibility of millions of qubits per square centimetre in advanced layouts.

Conversely, fabrication variability at the atomic scale can impact qubit reproducibility. Charge noise and valley splitting fluctuations in silicon must be carefully managed to ensure consistent qubit behaviour. Furthermore, cryogenic operation adds complexity to control and packaging systems.

Despite these hurdles, recent experimental achievements have brought spin qubits closer to practical application. Multi-qubit arrays with high-fidelity control, demonstrations of small error-correcting codes and integration with cryo-CMOS readout circuits all point to a promising roadmap.

1.2.6. Quantum annealing

Quantum annealing is a distinct quantum computing approach aimed at addressing combinatorial optimisation challenges by utilising quantum fluctuations to identify low–energy states in intricate systems. In contrast to gate–based quantum computing that performs arbitrary quantum logic operations, quantum annealers concentrate on lowering the energy of a specific cost function embedded in a quantum system's Hamiltonian. This method draws inspiration from traditional simulated annealing but is improved by quantum tunnelling processes (Kadowaki & Nishimori, 1998). The adiabatic theorem states that if the evolution occurs gradually, the system will stay in the ground state of the Hamiltonian in question, resulting in an optimal or nearly optimal solution (Albash & Lidar, 2018).

The leading commercial application of quantum annealing is created by D-Wave Systems, which has produced several generations of annealing hardware featuring up to 5000 qubits (King, et al., 2019). These devices are mainly designed for quadratic unconstrained binary optimisation (QUBO) challenges and Ising models, applicable in logistics, portfolio optimisation and machine learning. In contrast to universal quantum computers, quantum annealers function without the need for error correction and can operate on larger scales currently, though they have restricted programmability.

Although annealing does not enable universal computing, it offers a practical way to achieve quantum–enhanced performance in certain problem categories. Recent research indicated that hybrid classical–quantum workflows, like the D-Wave Leap platform, can surpass purely classical heuristics in a specific scenario (Aramon, et al., 2019).

Nevertheless, obstacles persist in evaluating benchmarks, adapting to versatile algorithms and contrasting outcomes across different devices.

1.2.7. Topological qubits

Topological qubits represent one of the most theoretically promising yet experimentally immature approaches to quantum computing. They aim to encode and manipulate quantum information using topologically protected quasiparticles, such as non-Abelian anyons, that exhibit resistance to local sources of decoherence. Among these, Majorana zero modes (MZMs), which can emerge in topological superconductors under specific conditions, are the most studied candidates for building topological qubits (Nayak, Simon, Stern, Freedman, & Das Sarma, 2008) (Karzig, et al., 2017).

The key idea is that when Majorana modes are spatially separated and braided, the resulting operations are inherently fault-tolerant, offering a pathway toward low-overhead, scalable quantum architectures. Unlike traditional qubits that require active error correction, topological qubits are designed to be passively robust against certain types of noise due to their non-local encoding.
Recent developments have renewed interest in this platform. In 2025, Microsoft's Majorana 1 prototype demonstrated an eight-qubit device built using hybrid In As Al topological materials. The project reported signatures consistent with Majorana behaviour, including parity-conserving operations and fermionic statistics, although definitive braiding evidence remains under peer review (University of California, 2025) (Aaronson, 2025).These results mark the first experimental step toward scalable topological quantum hardware.

Despite their conceptual appeal, topological qubits still face significant challenges. These include the reliable creation, control, manipulation of Majorana modes, the integration of these systems with readout and gate logic and the reproducibility of experimental results. Nonetheless, they remain a critical focus for long-term quantum computing roadmaps due to their potential for hardware-level fault tolerance.

As of today, topological qubits are not yet part of commercially available quantum devices, but continued investment, particularly from firms and academic centres focused on condensed matter physics, suggests that this technology could play a foundational role in the future landscape of error-resilient quantum computing.

1.2.8. Hardware platforms and application verticals

The variety of quantum hardware designs highlights that no single technology can currently address all computational areas effectively. Every platform offers distinct advantages and limitations, rendering it better suited for particular application areas, ranging from optimization and simulation to quantum machine learning or secure communication. Table 1 provides an overview of the relative positioning of key hardware technologies concerning these sectors.

Superconducting and trapped-ion qubits lead in short-term experimental and cloud-based systems, providing excellent gate fidelities ideal for algorithm testing and small-scale optimization, whereas photonic and neutral-atom platforms show significant scalability and potential for distributed architectures and quantum networking. Spin qubits offer compatibility with semiconductor manufacturing, indicating potential future benefits in large-scale integration and energy-efficient management. Quantum annealers, while not universal, are already providing practical outcomes in combinatorial optimization, whereas topological qubits continue to be a future goal for robust, large-scale computing.

Chapter 3 provides an in-depth examination of the precise alignment of hardware with industrial applications, like molecular simulation in chemistry, portfolio optimization in finance, or routing in logistics, assessing the technological maturity and economic significance of each sector.

Hardware platform	Strengths	Limitations	Application verticals
Superconducting qubits	Mature fabrication, fast gate operations, widely available via cloud (IBM, Google).	Require cryogenic temperatures, limited connectivity and scalability.	Algorithm testing, optimisation (QAOA), small-scale chemistry (VQE).
Trapped ions	Highest fidelities, long coherence, all-to-all connectivity in small systems.	Slow gate times, scaling limited by control complexity.	Quantum simulation, chemistry, high-precision algorithms.
Photonic qubits	Room-temperature operation, ideal for communication and distributed architectures.	Probabilistic gates, photon loss, limited error correction.	Quantum communication, quantum networking, sampling problems.

Neutral-atom qubits	Scalable arrays, natural parallelism, tunable entanglement (Rydberg).	Sensitive to laser noise, error correction still experimental.	Simulation of many-body systems, optimisation, materials design.
Spin qubits	CMOS-compatible, small footprint, potential for high-density integration.	Fabrication variability, cryogenic control required.	Long-term large-scale processors, hybrid HPC integration.
Quantum annealers	Commercially available, well-suited for combinatorial optimisation.	Not universal, limited problem mapping flexibility.	Logistics, scheduling, finance optimisation (QUBO problems).
Topological qubits	Intrinsically fault-tolerant, robust to local noise.	Still experimental, no scalable prototype yet.	Future universal, error-corrected computation across domains.

Table 1.1. : Hardware platforms and related strengths and limitations

This comparative viewpoint emphasizes that selecting hardware is a strategic as well as a technical decision because different platforms offer varying degrees of readiness, cost structures, and integration pathways, influencing which industries are most likely to see the first noticeable advantages of quantum computing. Aligning research priorities, investment roadmaps, and policy initiatives, topics that are further developed in Chapters 3 and 4, requires an understanding of these differences.

Even with advancements in specific hardware technologies, specialists repeatedly stress that it is still premature to identify a leading quantum computing platform. Participants from both academic and industrial sectors noted that although superconducting and trapped-ion systems presently excel in performance and commercialization, the field remains dynamic and investigative. Numerous participants emphasized that the idea of a "winner" is hasty, considering the simultaneous development of hardware, software, and algorithmic sophistication. As one industry expert remarked, "every technology is still uncovering its inherent domain of strength—superconducting qubits serve as dependable workhorses for algorithm prototyping, but neutral-atom and spin qubits could become more scalable when the engineering progresses.”

This careful viewpoint corresponds with factual data from business strategies and policy actions. By the year 2025, no single hardware architecture can be regarded as clearly superior. Industrial development data and research findings suggest that superconducting and trapped-ion technologies are expected to maintain their leadership until 2030, while neutral-atom and spin-based systems might become more significant from 2030 to 2040, and topological qubits are anticipated to be a long-term opportunity after 2040 (IBM, 2025) (Quantinuum, 2025)

The literature and interviews indicate that the sector is moving towards a multi-platform environment, where various hardware paradigms exist together, each optimized for specific functions, superconductors for general logic, trapped ions for precise operations, photonics for communication, and neutral atoms or spin qubits for scalability and hybrid integration. Instead of one prevailing technology, the new paradigm emphasizes functional specialization within a wider quantum ecosystem.

1.3. Readiness and level of maturity

The rapid advancement of quantum computing technology, coupled with growing public and commercial interest, as illustrated by the sharp increase in government and private funding discussed in Chapter 2. raises the fundamental question of how to accurately assess the maturity and readiness of quantum systems for practical use. A complicated and non-linear interaction of physics, hardware limits, algorithmic limitations and ecosystem dependencies characterises quantum computing, in contrast to classical digital technologies, which follow comparatively uniform technical trajectories.

Therefore, determining the degree of preparedness for quantum technologies is not just a technical task, but it is a strategic need. Decision-makers may assess the current state of the technology, how it might be linked to suitable industrial use cases and when it might provide real value by having a thorough understanding of maturity stages. Examining traditional maturity models like the Technology Readiness Level (TRL) framework and discussing their shortcomings in the context of quantum computing.

1.3.1. The Technology Readiness Level

The Technology Readiness Level (TRL) model, created by NASA and extensively used in engineering and industry R&D, is the conventional basis for evaluating technological maturity and evaluating the risks associated with its development and offers a common language and set of criteria for communication between researchers, engineers and decision-makers.

It consists of different steps, from the observation of fundamental principles (TRL 1) to complete implementation in operational situations (TRL 9). This model outlines a linear development through nine levels.

Here, all nine levels:

- TRL 1: basic principles are described or observed at the theoretical or experimental stage
- TRL 2: technological concepts are formulated and not yet necessarily tested
- TRL 3: proof of concept is carried out in a laboratory, at the level of the technical process
- TRL 4: the technology is validated in the laboratory
- TRL 5: a technology model in a production grade environment is created
- TRL 6: a technology prototype is demonstrated in an environment representative of the intended use case
- TRL 7: a prototype is evaluated in an operational environment
- TRL 8: a complete system has been evaluated and qualified
- TRL 9: a complete system is operational and qualified for production. ((WIPO), 2017)

The TRL ends at the deployment stage and ignores the full operational life cycle, as well as the technology's eventual obsolescence or relevance. Furthermore, TRLs tend to focus on technological maturity alone, neglecting market, organizational, or regulatory readiness, which are equally critical for real-world deployment.

Nilchiani suggest the Extended TRL (eTRL) methodology to fill this gap. It assesses post-deployment sufficiency by examining how well system performance, changing needs and external context align. In addition to providing a defined framework to assist lifetime decisions, upgrades or managed obsolescence, the eTRL adds five new levels (TRL 10 - 14). For complicated or long-lived systems where static readiness assessments are inadequate, this expansion is very helpful. (Nilchiani, Caddell, & Taramsari, 2025)

Considering the TRL 9-level scale, it is appropriate to consider that it provides a clear linear roadmap from early research to deployment, but it should not be interpreted rigidly. In practical use, TRLs must be adapted based on the type of innovation, whether it is a physical product, a software component, or a hybrid system and the context of testing.

Within the European Union, TRLs are embedded in major funding frameworks such as Horizon Europe and the EIC, serving as a bridge between research stages and industrial readiness. For complex, non-linear technologies like quantum computing, TRLs should be complemented by domain-specific indicators and critical assessments of the so-called “valley of death” between laboratory validation (TRL 4) and effective system integration (TRL 7), where many high-potential innovations risk stalling (Commission, 2022). This "valley of death" denotes the funding and development gap that arises between initial validation and scalable implementation. In this stage, technologies require resources and infrastructure beyond the scope of academic research, while still being too uncertain to attract private investment. As a result, many promising innovations remain stuck at intermediate readiness levels despite solid scientific foundations. The lack of clear market pathways and the hesitation of investors make this the phase of greatest risk, highlighting its strategic relevance in innovation policies and technology transfer. Positioned between publicly funded research and market-driven investment, the valley of death embodies not only a financial bottleneck but also a structural challenge affecting the effectiveness of innovation ecosystems, industrial competitiveness and the socio-economic returns of public R&D. To mitigate these risks, governments and organizations increasingly promote transitional funds, incubators and public–private partnerships to support technologies in their path toward commercialization.

This idea is depicted in Figure 4, which emphasises the funding disparity that usually arises between public backing for initial research and private investment in scalable commercialisation. As demonstrated, government and academic institutions usually finance the early phases of the innovation process (fundamental research, concept validation, lab production), whereas the private sector engages more significantly only in subsequent stages (prototype development, production settings, showcasing production capabilities). The intermediate gap is referred to as the “Valley of Death,” where numerous promising technologies do not progress due to the discrepancy between the needed resources and the investments that are accessible.

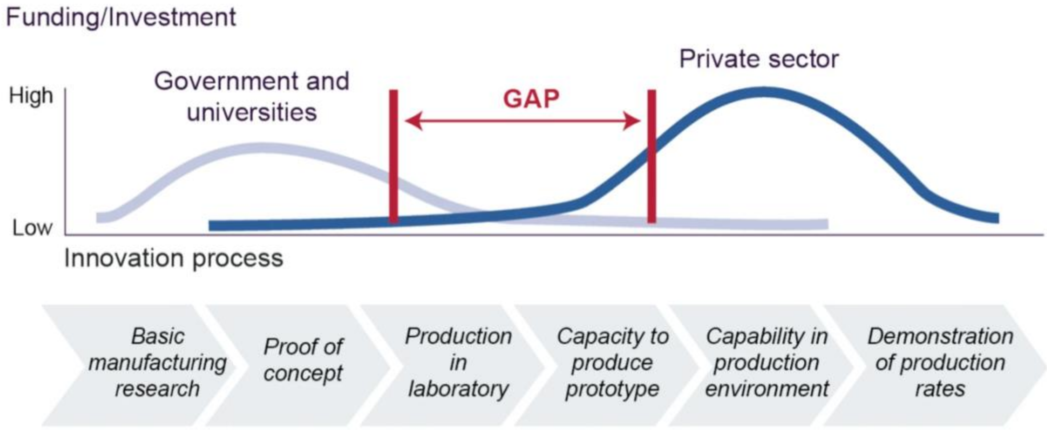

Figure 1.4.: The Valley of Death in the innovation process, showing the funding gap between government/university support and private sector investment (GAO, 2021)

1.3.2. Defining maturity in quantum computing

Despite the theory of technology readiness level, the development trajectory of quantum computing technologies is not linear, particularly those based on noisy intermediate-scale quantum (NISQ) devices. The phrase NISQ, coined by John Preskill in 2018 (Preskill J. , 2018), describes the present generation of quantum processors that have anywhere from several dozen to several hundred qubits. These systems are considered “intermediate-scale” as they surpass small lab prototypes but are still distant from the large, fault-tolerant machines anticipated for the future. They are considered “noisy” due to qubits and quantum gates being very susceptible to errors, having short coherence times and imperfect control processes. Consequently, calculations can be maintained only for limited circuit depths before noise surpasses the output. Although this limits their ability to run extensive algorithms or attain completely dependable outcomes, NISQ devices are still sufficiently robust to tackle issues that might be insurmountable for classical computers, including specific optimization challenges, sampling issues, or quantum simulations in chemistry and materials research. The hybrid application of these alongside traditional resources is central to many upcoming quantum algorithms, representing the technological edge where research, industry, and investments are presently concentrated.

It is challenging to evaluate their preparedness using standardised TRL scales since they instead display non-deterministic, multidisciplinary and hardware-dependent dynamics.

Evaluating the maturity of quantum computing technologies necessitates a more customised method than the conventional TRL scale provides. Quantum systems function operate significant noise, exhibit probabilistic characteristics and depend greatly on the simultaneous development of hardware and software. To address these challenges, the Quantum Technology Readiness Level (Q-TRL) framework has been developed to better assess the advancement of quantum technologies, especially during the Noisy Intermediate-Scale Quantum (NISQ) era (Purohit A. , Kaur, Seskir, Posner, & Venegas-Gomez, 2023).

Q-TRL maintains the structure of nine progressive levels while integrating quantum-specific metrics that reflect the real-world elements of quantum computing. These consist of:

- The number and arrangement of qubits are crucial, as the capacity to increase qubits while ensuring connectivity influences the practicality of intricate algorithms and error correction
- Timeliness reliability and gate precision, as even minor discrepancies in gate fidelity or timing quickly build up and undermine computational dependability
- Access to techniques for reducing or correcting errors is crucial for prolonging coherence times and advancing toward fault-tolerant systems
- Quantum capacity and performance metrics, including quantum volume or circuit layer operations per second (CLOPS), offer system-level insights into actual computational strength beyond merely counting qubits
- The readiness of software frameworks and hybrid orchestration layers is crucial, as the successful use of hardware relies on compatibility with traditional control systems, compilers and accessible programming environments

(Bharti, et al., Noisy intermediate-scale quantum (NISQ) algorithms, 2022)

In contrast to classical systems, quantum computing does not progress in isolation. A Q-TRL 4 system might show fundamental two-qubit operations but may not have enough error correction to progress past testing scenarios. A Q-TRL 6 system necessitates consistent multi-qubit entanglement, evaluated algorithmic executions and connection with software that facilitates practical usage.

Importantly, Q-TRL is not a one-size-fits-all answer. Different quantum technologies progress through diverse readiness pathways, highlighting their unique physical limitations and scaling approaches. For instance, superconducting qubits have achieved prototype-level showcases with industry backing, whereas photonic and topological methods are still in preliminary experimental phases. Additionally, a particular platform might be better suited for certain applications, like trapped ions in precise algorithms or neutral atoms in extensive simulations, compared to others (Purohit A. , Kaur, Seskir, Posner, & Venegas-Gomez, 2023).

Therefore, Q-TRL provides a modular, context-aware framework to evaluate the actual position of a quantum computing system regarding its deplorability and value generation. As the sector advances, embracing Q-TRL can aid in standardising industry metrics, shaping and directing strategic funding (Ezratty, 2022).

Although the application of frameworks like Q-TRL for assessing the maturity of quantum technologies is notable, numerous professionals and specialists in the field stress that it is neither practical nor significant to assign one, cohesive TRL to the entirety of quantum computing.

In this context, the so-called “Valley of Death” is especially pronounced for quantum technologies. Moving from proof-of-concept to deployable prototypes necessitates expensive infrastructure, extended development timelines and uncertain commercial uses, often dissuading private investment (Elevate Quantum , 2024).

Public initiatives have specifically aimed to tackle this obstacle: for instance, the U.S. National Quantum Initiative Reauthorization Act (2024) designates $2.7 billion to connect research with commercialization, while European initiatives like Horizon Europe Transition strive to offer mid-stage assistance (Swayne M. , National, Quantum Computing Business, Research, 2024).

In comparison to other advanced fields like biotechnology or traditional semiconductors, the Valley of Death for quantum technologies is notably profound. This results from the distinctive mix of highly expensive infrastructure needs, such as cryogenics, ultra-stable lasers and specialized electronics, the lack of immediate commercial uses with evident returns and the reliance on global supply chains for specific components. These structural challenges increase the complexity of moving from lab confirmation to scalable models, positioning quantum as an exceptional instance within the wider innovation environment.

Various quantum platforms exhibit differing capabilities in overcoming this crucial threshold. Superconducting qubits, propelled by industry giants like IBM and Google, take advantage of established supply chains and defined scaling strategies, positioning them as the most developed options. Trapped ions, although operating gates at a slower pace, demonstrate exceptional fidelities and can currently be utilized via commercial cloud services, indicating robustness across intermediate Q-TRLs (Poindexter, 2025). Neutral atoms are becoming increasingly viable scalable options: QuEra secured more than $230 million in early 2025 (QuEra, 2025), whereas Infleqtion revealed a $50 million public–private collaboration in Illinois to construct a utility-scale neutral-atom quantum computer (Reuters, Quantum computing startup QuEra closes $230 million funding round, 2025). Google’s Willow processor achieved a milestone by reaching below-threshold error correction, signifying an important advancement toward logical qubits; however, difficulties still exist in converting lab results into real-world applications (Hartmut, 2024).

Photonic systems, while not as developed in error correction, are viewed as promising due to their suitability for telecom infrastructure. In contrast, topological qubits are still very speculative, with experimental advancements at very low levels of readiness. Ultimately, cloud access has become a factor in addressing the Valley of Death: platforms like Amazon Braket and Microsoft Azure Quantum make early-stage devices more accessible, expand the user community, and speed up software–hardware co-design, thus minimizing the risk of stagnation between Q-TRL 4 and Q-TRL 6.

According to the Executive Account Manager at QuEra Computing, interviewed on July 14, 2025, the preparedness should be evaluated through various, context-based perspectives that illustrate the complex and changing characteristics of the technology. From a hardware viewpoint, quantum computing has shown consistent and observable advancements during the last ten years. Systems like superconducting qubits and trapped ions have achieved reliable performance in experiments, showing consistent improvements in gate accuracies and quantum volume each year. In this context, the Technology Readiness Level (TRL), defined as the practicality and integration of physical qubit designs, can be viewed as being in the medium range (TRL 4 - 6), varying based on the platform and specific application. In comparison, from the perspective of industrial use and business acceptance, the degree of preparedness is still notably lower. Although there are a few pilot projects currently in place, particularly in areas like finance, chemistry, and logistics, these projects are frequently confined to simulated environments or small-scale trials conducted under optimal circumstances. The absence of a clear algorithmic edge in many real-world situations, along with the lack of strong workflows that integrate quantum and classical computing, results in application-level Technology Readiness Level (TRL) typically being in the initial phases, often not surpassing TRL 3. This difference underscores the necessity for a two-pronged maturity evaluation that distinguishes between technological readiness (t-TRL) and application readiness (a-TRL). Stakeholders can only achieve a clear understanding of the current state of quantum computing and what is needed to transition from potential to actual use by examining both aspects.

A major limiting factor for both dimensions is the presence of noise and decoherence, which fundamentally restricts the complexity and depth of algorithms that can be carried out on existing quantum hardware.

A potentially effective long-term solution to this problem is the creation of quantum error correction (QEC). This technique allows for the construction of logical qubits from physical qubits, significantly enhancing the reliability of the system. The idea is to represent one logical qubit over a vast collection of physical qubits, enabling the detection and correction of errors resulting from decoherence or faulty gate operations without erasing the quantum information. One of the most researched methods is the surface code, which achieves fault tolerance as long as the physical error rate stays under a specific threshold (approximately 1%). Nonetheless, executing QEC is highly resource-demanding: achieving a single logical qubit might necessitate hundreds or even thousands of physical qubits, contingent on the hardware's fidelity. In spite of this overhead, advancements in showcasing below-threshold error rates, like Google's Willow processor in 2024, signify an important move towards scalable fault-tolerant designs. Ultimately, QEC is viewed as essential for attaining practical quantum advantage in real-world applications, as it facilitates deep circuits and extended algorithm runtimes that are presently unfeasible on noisy NISQ devices.

Nonetheless, applying quantum error correction (QEC) demands considerable additional resources concerning the number of qubits and the accuracy of control, thereby adopting a gradual, foundational approach, wherein the hardware needs to develop to facilitate fault-tolerant computing. Simultaneously, a top-down strategy is being followed, where algorithm creators strive to design quantum algorithms that use resources more efficiently, specifically, algorithms that need fewer gates, have simpler circuits, or can better withstand noise. This mutual development between hardware engineering and algorithm innovation demonstrates the complex aspects of being prepared for quantum technologies and reinforces the need for distinct Technology

Readiness Levels (TRL) based on the maturity of technology and its applications (Anonymous, 2025).

1.4. Strategic implications for enterprises

Quantum computing is rising not just as a scientific and technological advance but also as a sustainable strategic tool for businesses pursuing competitive edge, innovative pote ntial and operational change. Nonetheless, the impact of quantum technologies on business intricates, encompassing unpredictability, disjointed ecosystems and changing performance benchmarks. To understand this complexity, Jekins suggests a strategic framework consisting of four unique interconnected enterprise strategies: conventional, options, discovery and adversarial. (Jenkins, Berente, & Angst, 2022)

Businesses adopting a conventional strategy seek to enhance current processes or address traditional issues more effectively by utilising quantum tools. This encompasses uses like route optimisation in logistics, energy network simulations, or portfolio optimisation domains where combinatorial complexity restricts traditional methods. Here, quantum is not disruptive but incremental, improving efficiency where classical tools struggle with combinatorial complexity.

An alternative method, the options strategy, embodies a future-oriented investment rationale. Companies invest in employee training, testing proofs of concept and forming alliances with hardware and software vendors, even without anticipating immediate benefits. This resembles obtaining real options: by investing early, firms gain the ability to expand as the technology achieves greater readiness stages. Instances involve pharmaceutical corporations collaborating with quantum startups to get ready for upcoming advancements in molecular simulations.

The discovery strategy focuses on fostering completely new capabilities. In this context, quantum computing serves as an investigative instrument to reveal once unreachable insights, such as simulating intricate molecular structures for pharmaceutical advancements or materials development. From this viewpoint, quantum serves not merely as a tool for efficiency but as a catalyst for new business models and industries.

Ultimately, the adversarial approach relies on defensive positioning: firms utilise quantum technologies to prevent being strategically surpassed by rivals. Companies investigate quantum technologies not solely to capitalise on them right away, but to prevent lagging behind rivals or facing disruption. This is particularly significant in finance and cybersecurity, where possible advancements, like quantum decryption, might generate unequal risks. The shift towards post-quantum cryptography exemplifies this protective reasoning.

These four approaches emphasise an essential realisation: quantum computing will not provide a universal path for everyone. In contrast, organisations should synchronise their quantum initiatives with their overall innovation objectives, industry trends and internal preparedness. Early adoption involves more than just being technically prepared; it also encompasses strategic intention and the gradual development of capabilities (Jenkins, Berente, & Angst, 2022) (World Economic Forum, 2022).

Besides opportunities, quantum computing brings new dimensions of strategic risk. A commonly referenced issue is the uncertainty regarding the timeline to achieving quantum advantage, which makes return - on - investment projections and technology planning more difficult. Additionally, the sector is significantly divided, lacking an agreement on leading hardware platforms or software standards, which raises the chances of vendor lock–in or sunk–cost risk (Capgemini Research Institute, 2022).

Cybersecurity is another critical element to consider. Quantum computing presents a significant risk to existing public-key cryptographic systems like RSA and elliptic-curve cryptography, anticipated to be exposed once large-scale fault-tolerant computers are developed. This viewpoint has quickened the advancement of post-quantum cryptography (PQC). In August 2024, the U.S. National Institute of Standards and Technology (NIST) published its initial three PQC standards, FIPS 203 (CRYSTALS-Kyber), FIPS 204 (CRYSTALS-Dilithium), and FIPS 205 (SPHINCS+), and in March 2025, HQC was incorporated as a secondary algorithm (NIST, 2024).

Businesses are being advised to get ready for “harvest-now, decrypt-later” attacks, where encrypted information obtained now may be revealed when quantum decryption becomes possible (Sectigo, 2025). Industry analyses indicate that only a small fraction of organisations are presently “quantum-safe champions,” while the majority still do not possess crypto-inventories, migration roadmaps, or strategies for crypto-agility (Woollacott, 2025). National cybersecurity agencies have highlighted the importance of prompt migration: for instance, the UK’s NCSC recommends that organisations strategies by 2028, start their transition by 2031, and finalise it by 2035 to prevent significant vulnerabilities (Fadilpašić, 2025). Strategic models like QUASAR (2025) recommend that companies utilise staged methods, integrating readiness assessments, operational metrics, and gradual execution, to facilitate this transformation successfully (Weinberg, 2025).

Simultaneously, realising quantum value necessitates interdisciplinary expertise and considerable internal preparedness. The World Economic Forum (2022) underscores that quantum capability is more than a technological resource; it also presents a challenge related to human capital. Businesses should focus on training, collaborations and internal knowledge sharing to create a sustainable quantum workforce.

These elements underscore the necessity for a quantum readiness evaluation that extends past technical standards and takes into account organisational framework, cybersecurity stance, vendor approach and training initiatives. Companies that actively tackle these aspects will be more equipped to manage the unpredictability of the quantum age while ensuring sustained innovation benefits.

To gain a clearer insight into how companies are managing the complexities of quantum computing, experts suggest a tiered model of Quantum Computing Business Ecosystem. As shown in Figure 5, this ecosystem consists of several interconnected layers, ranging from hardware and infrastructure to delivery methods, strategic approaches and application areas.

Every layer represents an essential dimension of capability enhancement:

- Hardware includes platform–specific architectures like superconducting or trapped–ion systems
- Infrastructure encompasses the quantum software stack, control mechanisms and error correction techniques
- Delivery models vary from quantum access through the cloud to hybrid integrations supported by consultants
- Strategy is expressed through four categories: conventional, options, discovery and adversarial, each representing a unique approach to value creation and competitive stance

- Applications occupy the highest position, supported by the underlying foundational layers.

The comprehensive perspective emphasises that no single element is sufficient on its own. Strategic alignments necessitate a synchronised advancement across technical and organisational areas, in addition to integration with cloud services, talent pipelines, and industry partnerships. Companies employing a “partial–stack” strategy need to work alongside vendors and consultants to address capability deficiencies, whereas “full–stack” entities invest vertically to dominate the whole chain (Jenkins, Berente, & Angst, 2022).

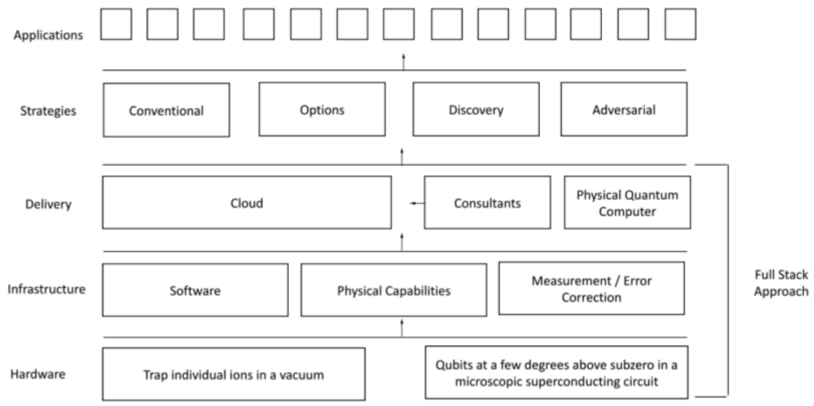

Figure 1.5.: Quantum computing business ecosystem (Jenkins, Berente, & Angst, 2022)

1.5. From business challenge to quantum implementation

The earlier section detailed the framework of the quantum computing business ecosystem, but it is equally vital to specify what it tangibly entails to utilize and program a quantum computer to solve a problem. Currently, quantum computers function not as isolated devices but as parts of hybrid processes where traditional systems manage, direct, and analyse calculations performed on quantum hardware accessed remotely via cloud services like IBM Quantum, Amazon Braket, or Microsoft Azure Quantum (Swayne, 2025) (Microsoft Quantum, 2025) (IBM, 2025) (Preskill, Quantum Computing in the NISQ era and beyond, 2018).

The process starts with defining the problem, where a business or scientific issue, like route optimization, risk assessment, or molecular modelling, is converted into a mathematical representation appropriate for quantum algorithms. Based on the goal, the formulation could be a Quadratic Unconstrained Binary Optimization (QUBO) issue, a Hamiltonian that represents a physical system, or a dataset represented in quantum states for machine learning.

Developers utilize software frameworks like Qiskit, Cirq, or PennyLane to create quantum circuits or variational algorithms. These applications, usually developed in Python, outline sequences of quantum gates that adjust qubits to investigate intricate solution spaces (Cirq, 2025) (Bergholm, 2022).
The circuit is then transpiled, modified to fit the gate set and connectivity limitations of the intended hardware, be it superconducting, trapped-ion, or photonic, aimed at reducing circuit depth and error build-up.

Execution is essentially stochastic: the identical circuit is executed thousands of times (shots), and the resulting measurement distributions are combined to approximate observables or cost functions. In the present noisy intermediate-scale quantum (NISQ) era, the most effective algorithms are hybrid variational types, like the Variational Quantum Eigensolver (VQE) for chemical applications or the Quantum Approximate Optimisation Algorithm (QAOA) for combinatorial issues, where a classical optimiser adjusts parameters governing the quantum circuit and obtains feedback from measurement results These algorithms and their industrial implications will be further discussed in Chapter 3. Techniques for mitigating errors, such as calibration, extrapolation, and probabilistic error cancellation, are utilized to address noise until completely fault-tolerant architectures are accessible.

From an organizational perspective, programming a quantum computer involves coordinating a multi-tiered procedure:

- articulating the value proposition and creating a traditional benchmark for evaluation
- translating goals and limitations into suitable mathematical representations (QUBO, Hamiltonian, or state encoding)
- choosing back-end hardware and toolsets compatible with connectivity and depth constraints
- creating the combined optimization cycle

- assessing typical cases with traditional solvers while utilizing established kill-or-scale benchmarks for investment choices.

These activities necessitate cross-disciplinary teams, quantum engineers, data scientists, software architects, and business stakeholders, and integration with current IT systems via APIs, data pipelines, and governance structures that oversee job costs, queue priorities, and risks associated with vendor lock-in (World Economic Forum , 2022)

A standard optimization workflow typically includes: preprocessing and reducing the problem (e.g., clustering or decomposition), creating the QUBO by adding penalty terms for constraints, embedding onto hardware topology (for annealers) or defining the ansatz and cost function (for gate-based systems), performing iterative evaluations and updating parameters until convergence and validating with advanced classical heuristics or mixed-integer programming (Phillipson, Quantum Computing in Logistics and Supply Chain Management an Overview, 2025) (Ajagekar & You, Quantum computing for energy systems optimization: Challenges and opportunities, 2020).

In quantum simulation, VQE evaluates energies and electronic characteristics through shallow circuits and collaborative design between quantum and classical processors, whereas in a prospective fault-tolerant framework, Quantum Phase Estimation (QPE) will facilitate chemically precise modelling of intricate molecules and materials (Bauer, Bravyi, Motta, & Chan, Quantum algorithms for quantum chemistry and quantum materials science, 2020).

In conclusion, the present application of quantum computing does not align with completely implemented production workloads; instead, it illustrates a process of developing capabilities and accurately defining problems within regulated hybrid workflows managed by comparative metrics and decision limits. This viewpoint links the ecosystem mentioned earlier to the sectoral applications explored in Chapter 3: the generation of value currently relies more on aligning problem definition, technical resources, and governance frameworks with both physical constraints and strategic goals than merely on the availability of qubits (Preskill 2018; World Economic Forum 2022).

1.6. Quantum supremacy, quantum advantage and hybrid advantage

As quantum computing has advanced, three important criteria, such as quantum supremacy, quantum advantage and hybrid advantage, have been proposed to evaluate its transformational potential.

These terms, although commonly found in scientific and industrial discussions, frequently confuse more than they explain. A thorough evaluation shows that every concept contains unresolved ambiguity, fluctuating thresholds and considerable practical constraints, especially when considered from an enterprise or strategic perspective.

Quantum supremacy signifies a quantum computer's ability to tackle a problem that classical supercomputers cannot solve, regardless of the practical significance of the issue. The definitive illustration was Google's Sycamore experiment in 2019, which performed a random circuit sampling task in 200 seconds, an undertaking thought to require thousands of years on a traditional computer (Arute, et al., 2019). Nonetheless, this accomplishment was primarily emblematic, later research has demonstrated that traditional techniques, utilising tensor networks and optimisation heuristics, can yield approximations of these outcomes within hours or days on high-performance clusters (Pan, Chen, & Zhang, 2022) (Zlokapa, Villalonga, Boixo, & Lidar, 2023).

To complement the literature, interviews were conducted with experts, including researchers, innovation managers and industry practitioners, in order to provide first-hand insights into how the notion of quantum supremacy is perceived in practice. Multiple participants remarked that, even with the prominence of Google's 2019 Sycamore experiment, true quantum supremacy has not been attained yet. They emphasised that later classical developments have swiftly contested the initial assertions, indicating that supremacy is more of an evolving aim than a fixed achievement. From their viewpoint, the depiction of "supremacy" in public discussions is more influenced by marketing tactics and investment stories than by strong scientific proof. Specifically, participants noted that revelations presented as breakthroughs are occasionally employed to generate excitement and secure funding, instead of indicating verifiable advancements with practical industrial use. This viewpoint corresponds with critiques in scholarly writings that caution against merging symbolic showcases with genuine technological preparedness. The interviews thus emphasise the need to differentiate between symbolic successes, which might attract media attention and meaningful progress that can be measured, replicated and connected to real business value.

Demonstrations of supremacy, hence, lack direct relevance to industry and have been criticised as artificial benchmarks with restricted translational significance.

Quantum advantage, on the other hand, signifies an improvement in tackling practically significant problems. Quantum advantage represents both a theoretical landmark and a tangible enhancement in addressing significant real-world challenges relevant to industry and society. In contrast to "quantum supremacy," which indicates a quantum machine executing a task impossible for any classical computer, even if the task is artificial or of minimal usefulness, quantum advantage suggests that a quantum computer can solve problems of true economic or scientific significance more effectively than the top classical techniques available. This could result in quicker logistics optimisation, more precise simulations in chemistry and materials science, or enhancements in financial modelling. Obtaining quantum advantage necessitates both advancements in hardware, like scalable qubit architectures and error correction and the co-development of algorithms and software stacks designed for particular applications. Consequently, quantum advantage is regarded as the moment when quantum technologies shift from mainly being research-focused to providing tangible business and societal benefits.

By 2025, there is still no agreement on a confirmed industrial example where quantum techniques surpass classical approaches in terms of cost, accuracy and scalability.

Advancements have occurred in specialised areas like quantum chemistry, where hybrid algorithms such as VQE can determine molecular energies using circuits of reduced depth (Bharti, et al., Noisy intermediate-scale quantum (NISQ) algorithms, 2022).

Significant recent advancements comprise the Greedy Gradient-Free Adaptive VQE, which attained more than 98% fidelity in calculating a 25-body Ising ground state on a 25-qubit quantum processor (Feniou, Hassan, & Claudon, 2025) and the inaugural photonic, room-temperature VQE execution for hydrogen employing silicon-photonics (Baldazzi, 2025). Qunova's HI-VQE is now offered on IBM's Qiskit Functions Catalog, providing up to 1,000× improved efficiency for molecular modelling (Swayne M. , 2025). Studies on benzene using VQE reveal existing hardware constraints that need to be addressed for scalability (Carreras, Casanova, & Orús, 2025), whereas new quantum-neural hybrid approaches, utilised for the isomerisation of cyclobutadiene, have attained near-chemical accuracy and demonstrate significant robustness to noise (Li, et al., 2025). However, these outcomes frequently depend on particular hardware configurations, customised approaches and meticulous noise management, emphasising the disparity between proof-of-concept showcases and large-scale industrial implementations.

Nonetheless, these outcomes frequently rely on simplified noise assumptions or tailored tuning for specific domains. In optimisation and machine learning, traditional heuristics continue to prevail in terms of both adaptability and reliability.

To better understand how these dynamics are viewed in practice, interviews were carried out with quantum researchers, innovation leaders and technical managers. A clear message was conveyed: quantum supremacy has not been realised yet and reaching it will probably demand several additional years of continuous technological progress. Interviewees highlighted that although hybrid quantum–classical architectures present the most practical near-term strategy, their influence should be seen as a component of a wider learning process rather than an instant upheaval. Hybrid systems, in which quantum processors act as dedicated accelerators in classical high-performance computing setups, were considered crucial for initial adoption initiatives. This viewpoint corresponds with the existing condition of Noisy Intermediate-Scale Quantum (NISQ) devices, which do not possess the fidelity and scalability required for independent quantum computing.

However, measurable performance improvements are still limited and reliant on context. Interviewees emphasised that although hybrid strategies offer a chance to investigate use cases and develop in-house skills, the applicability on an industrial scale remains restricted, and meaningful benchmarking is obstructed by variations in platforms and challenges with reproducibility.

Notably, any interviewees conveyed their uncertainty regarding the concept of “hybrid.” Given that all existing quantum devices depend on classical controllers and processing units to function, they wondered if the difference between “pure” and

“hybrid” systems has any conceptual significance. This uncertainty additionally illustrates the nascent state of the field, in which both technical definitions and strategic interpretations are still developing.
Recent scientific attempts have sought to provide clarity to these uncertainties. Specifically, (Lanes, et al., 2025) suggest a methodical and thorough framework for evaluating quantum advantage in practical terms. Their model highlights three criteria: the task should have practical significance, the output needs to be verifiable and the quantum-classical distinction must be quantifiable. The authors emphasise that numerous previously asserted benefits have subsequently been disproven by enhanced classical algorithms. They assert that benchmarks should be publicly accessible, reproducible, and collaboratively developed by experts in both classical and quantum fields. The framework highlights three potential problem categories, sampling, variational and expectation-value estimation, where quantum devices could show an advantage given specific technical assumptions. Nonetheless, the writers warn that, even in these specific areas, reliable assertions of quantum superiority should depend on thorough error measurement and hybrid evaluations against classical supercomputing standards.

Additionally, the meaning of "advantage" is changing, as traditional computing progresses, particularly through AI-driven simulation and optimisation, the standard for quantum evaluation changes. This situation causes quantum advantage to be a fluctuating objective. Multiple experts cautioned that excessive enthusiasm regarding quantum preparedness may result in misguided investments and impractical industrial anticipations. In summary, although discussions regarding quantum supremacy and advantage continue to be intellectually and strategically engaging, the present situation involves hardware vulnerability, algorithmic underdevelopment, and intricate integration requirements. Hybrid models present a feasible way forward, yet their function should be viewed as strategic experimentation rather than operational change. For industrial stakeholders, success will rely more on cultivating adaptive abilities and incremental innovation approaches suited to quantum's slow and inconsistent development, rather than predicting transformative performance.

1.7. Conclusions of the first chapter

Finally, a schematic overview of Chapter 1 is given in Table X. It provides an overview of the chapter's progression from the theoretical underpinnings of quantum computing to the managerial and strategic ramifications for businesses. This well-organized perspective demonstrates how every technical aspect, from readiness frameworks to qubit physics, contributes to comprehending quantum technologies as both organizational and scientific breakthroughs.

Pillar	Core idea	Managerial takeaway
Quantum principles	Non-classical computation is made possible by qubits, superposition, entanglement, and interference.	Quantum ≠ faster classical: value is not determined by clock speed but rather by a different physics.
Hardware platforms	Superconducting, trapped-ion, photonic, neutral-atom, spin, annealing, topological.	There isn't a winner yet; instead, hardware is chosen based on maturity and use case (multi-platform future).
Readiness and maturity	TRL/e-TRL adapted to Q-TRL; NISQ limits; valley of death between lab and scale.	Monitor t-TRL versus a-TRL and make plans for partnerships and phased funding to close the gap.
Workflow	Hybrid cloud workflows; QUBO/Hamiltonian mapping; VQE/QAOA; transpiration and shots.	Consider QC as a service: use kill/scale gates, benchmark against classical, and integrate via APIs.
Advantage concepts	Supremacy (symbolic), Advantage (useful), Hybrid advantage (near-term).	Prioritize reproducible benchmarks and problem-level advantage over headlines.
Strategy for firms	There are four positions: adversarial, options, conventional, and discovery.	While securing PQC for defensive needs, start with options (pilots, skills).
Security	NIST PQC standards; "harvest-now, decrypt-later" risk.	Create a roadmap for the migration and crypto inventory right away;

		compliance and governance are important.

Chapter 2 The European quantum landscape

2.1. Global landscape strategies

Quantum technologies have changed over the last ten years from being largely an academic field to one that is now a source of strategic and geopolitical competition.

In addition to facilitating scientific advancement, governments now see quantum computing, communication and sensing as essential elements of industrial competitiveness, digital sovereignty and national security. The United States, China, and the European Union are the three main blocs that are increasingly influencing the global race. Each of these blocs is pursuing unique funding schemes, governance models and industrial ecosystems that are reflective of larger political and economic ideologies.

The market-driven, innovation-led model used in the US is based on adaptable public-private partnerships. Long-term research is coordinated by federal organizations like the National Science Foundation (NSF), the Department of Energy (DOE), and DARPA, while commercialization is driven by private companies and venture capital. A ten-year federal investment of over $15 billion, divided among research centers, startups, and national laboratories, is anchored by the 2018 National Quantum Initiative Act, which was renewed and expanded in 2023.

The United States' approach is distinguished by: a robust venture capital ecosystem that includes major players like Andreessen Horowitz, DCVC, and Playground Global funding firms like IonQ, Rigetti, and PsiQuantum, a federal coordination through the National Quantum Coordination Office (NQCO), which ensures policy alignment across agencies, and a distributed industrial base that connects software startups with quantum hardware.

The US is the most dynamic market for quantum entrepreneurship because of this environment, which encourages rapid prototyping, risk-taking and scale-up potential. The dependence on private capital also contributes to cyclical volatility and strengthens the power of a small number of tech behemoths that set standards and manage infrastructure.

China, on the other hand, takes a state-led and security-focused stance. The nation's 14th Five-Year Plan (2021–2025) and the long-term Science and Technology 2030 Agenda both specifically mention quantum technologies, defining quantum information science as a foundation of economic leadership and national security.
Over $15 billion in Chinese investment has been made, mostly through state-owned businesses, the Chinese Academy of Sciences (CAS), and the Ministry of Science and Technology.
The strategic priorities are dual-use applications, which combine military and civilian goals under a single oversight, vertical integration of the entire value chain, from chip fabrication and cryogenic systems to quantum communication satellites, and the creation of a national quantum network, which has been in operation since 2021 and connects Beijing, Jinan, Hefei, and Shanghai via quantum key distribution (QKD).
Although China's "whole-of-state" model guarantees quick industrial consolidation and scaling, it restricts international cooperation, openness, and private sector flexibility. Its achievements in QKD-based infrastructure and photonic communication demonstrate the geopolitical ramifications of quantum sovereignty, wherein technological prowess directly translates into strategic influence.

The European Union follows a cooperative, multilateral and sovereignty-oriented approach, falling somewhere between these two models. In order to create a quantum ecosystem by design as opposed to through centralized control or unadulterated market competition, Europe's strategy places a strong emphasis on research excellence, ethical governance, and interoperability.
Instead of concentrating only on qubit supremacy, Europe's goals prioritize: establishing shared infrastructures under programs like EuroQCS and EuroHPC JU, which guarantee access to hybrid quantum–classical systems throughout the continent, fostering cross-border collaboration through flagship programs like Horizon Europe, Digital Europe and the Quantum Flagship, and integrating industry, academia and public policy to promote sustainable growth and technological independence.
Europe's global competitiveness may be constrained by its continued difficulties in securing a unified market for scale-ups, accelerating technology transfer, and mobilizing private capital.

Other international players play significant complementary roles in addition to these three blocks. With the help of METI's Quantum Technology Innovation Strategy and businesses like Toshiba, Fujitsu, and NEC, Japan continues to lead the world in quantum sensing and superconducting hardware. Canada serves as a link between the innovation networks of North America and Europe, is home to D-Wave, Xanadu, and Photonic Inc., and combines government funding with a thriving startup ecosystem.
The Asia-Pacific quantum corridor is strengthened by Australia and Singapore's significant investments in specialized hardware and quantum education.
These secondary hubs strengthen international cooperation on quantum standards, ethics, and interoperability while also aiding in the diversification of global supply chains.

2.2. European public investments and strategies

In this global context and in the rapidly evolving global competition to leverage quantum technologies, the European Union has emerged as a key institutional player, striving to merge research excellence with strategic independence. The EU is adopting a cooperative and multilateral strategy focused on synchronised public spending and sustainable infrastructure growth in contrast to China's security-centred, state-driven model and the US's venture capital-driven innovation approach. (European Commission, 2023). Nonetheless, in spite of these initiatives, the total degree of financial dedication stays relatively low, putting Europe in danger of lagging behind its international rivals in terms of overall investment potential.
This method is based on the recognition that quantum computing, in conjunction with quantum communication and sensing, constitutes a category of general-purpose technologies (GPTs) that can revolutionise various industrial sectors, like cryptography, pharmaceuticals, finance and climate modelling (World Economic Forum , 2024). Nevertheless, the EU's involvement in this competition is also characterised by a feeling of strategic weakness. The reliance on non-European quantum technology and cryogenic electronics, combined with the absence of local cloud infrastructure for quantum access, has raised significant concerns regarding Europe’s digital sovereignty ((QuIC), 2023).
Moreover, fragmentation among member states, restricted private investment and slow technology transfer processes have consistently been recognised as obstacles to scalability and industrial adoption (OECD, A quantum technologies policy primer,

2025). These structural vulnerabilities may lead to prolonged reliance on external suppliers, especially from the US and China, for hardware parts and cloud-based quantum solutions. The lack of a unified market for venture capital and scale-up financing hinders Europe's capacity to transform research excellence into industrial dominance. To tackle these challenges, it will be essential to enhance cross-border integration, implement targeted investment strategies and establish public–private partnerships that can expedite technology transfer and decrease dependency on non-European infrastructures.

These structural issues emphasise the necessity for enhanced collaboration among academic research, industrial application and policy alignment at the European level.

To address these constraints, the EU has implemented an extensive plan of strategic initiatives. Initiated in 2018 with a budget of €1 billion, the Quantum Flagship fosters multi-year innovation and research in essential areas, including quantum computing, quantum simulation and communication (Flagship, 2025). This initiative is now strengthened by Horizon Europe, the Digital Europe Programme and the EuroQCS project under the EuroHPC JU, which aims to implement quantum computers in combination with high-performance classical systems by 2025 (EuroHPC JU, 2024).

Furthermore, the European Commission has recently expressed its aim to establish the EU as a worldwide leader in quantum technology by 2030, based on three key technological pillars: quantum communication, quantum computing and quantum sensing and metrology. These initiatives are integrated into the EU's broader digital sovereignty goals and are managed through programs such as the European Quantum Communication Infrastructure (European Commission, European Quantum Communication Infrastructure (EuroQCI), 2025), as well as cooperative projects with the Quantum Industry Consortium (Quantum Industry Consortium, 2025).

The Commission highlights the significance of standardisation, cloud access and European-wide integration. It has encouraged the creation of collaborative quantum infrastructures, available through cloud platforms, aimed at research organisations and small to medium-sized enterprises. An updated Quantum Competence Framework and enhanced policy coordination with the European Chips Act seek to integrate quantum technologies into the strategy for Europe's essential digital infrastructure (European Commission, European Chips Act official website, 2025). In this context, policy coordination is vital for guaranteeing that Europe's diverse quantum initiatives develop cohesively instead of in isolated silos. The presence of various funding schemes and national programmes necessitates alignment to prevent duplication and fragmentation, while standardised norms and interoperable infrastructures are crucial for establishing a true single market for quantum technologies. The Commission has aimed to enhance governance structures and cross-border integration, also by engaging industry platforms like the Quantum Industry Consortium (QuIC). However, experts indicate that in the absence of more robust tools to align national strategies and attract private funding, competing initiatives could lessen the overall effect and impede Europe's ability to achieve its 2030 quantum leadership goals.

The initial operational system, PIAST-Q in Poland, employs trapped-ion technology and incorporates hybrid computing features, marking a significant achievement in Europe's attempt to connect classical and quantum resources. Comparable systems are being developed in France, Italy, Germany, Spain and the Czech Republic.
Additionally, the European Quantum Flagship has launched new KPIs and inclusion metrics for 2025 to track project advancement, ecosystem inclusiveness and industrial participation. These indicators offer a systematic assessment of technological preparedness and consistency with strategic objectives (Quantum Flagship, 2025).
Simultaneously, projects like EuroQHPC-Integration have been initiated to guarantee interoperability among quantum systems implemented throughout Europe. This project aims to establish common APIs, benchmarking tools and cloud accessibility standards to guarantee a uniform user experience and promote cooperative development among Member States (Poznań Supercomputing and Networking Center (PSNC), 2025).

From an industrial strategy viewpoint, the EU has recognised the necessity to attract private investment and keep quantum startups in Europe. In 2025, the European Commission launched a Quantum Scale-Up Fund and suggested a new legislative structure, the Quantum Act, designed to strengthen Europe's technological independence and tackle the capital market fragmentation that presently impedes startup development and competitiveness. As of 2025, the Quantum Act has not yet been adopted; the European Commission presented it within the Quantum Europe Strategy as a forthcoming legislative proposal, expected to be formally introduced in 2026 (Directorate-General, 2025).

The Quantum Act extends beyond financial tools: it creates a unified legal system to aid quantum startups throughout EU member states, introducing initiatives like a European Quantum Startup Label, easier access to publicly funded infrastructures (EuroQCS systems) and specific tax incentives for investors in quantum enterprises. It aims to synchronise public procurement procedures and simplify certification criteria to expedite the commercialisation of quantum technologies. The Act tackles persistent obstacles to scaling by promoting international cooperation and reducing market fragmentation (techUK, 2025).
Additionally, it is intended to connect with current initiatives such as the Chips Act and Horizon Europe, fostering synergies within Europe's digital objectives. Certain early critics, however, emphasise the necessity for more defined eligibility standards and wider involvement with SMEs to prevent preferential treatment for just well-capitalised scale-ups. Tackling these issues necessitates a more robust human-capital aspect: guaranteeing that access to opportunities is complemented by a well-trained workforce capable of engaging in and reaping benefits from emerging quantum initiatives. The increased focus on education and employment preparedness is clear in the revised Quantum Competence Framework, which outlines key skills, job roles and training routes crucial for expanding the quantum talent pool in Europe. This framework is supported by synchronised efforts with national education systems and industry partners to guarantee consistency between academic programs and upcoming labour market needs (Quantum Flagship, 2024).

In addition, Europe is progressing toward a thorough and progressively unified quantum approach that includes research, infrastructure, regulation and education. This initiative takes shape through significant projects like Horizon Europe, the Quantum Flagship, and EuroQCS within the EuroHPC JU, along with specialized resources such as the Quantum Scale-Up Fund and the Quantum Competence Framework. Ongoing obstacles persist, disconnected national plans, lack of private funding, and reliance on non-European technology and cloud systems, but the direction is becoming more defined. Through strengthening international collaboration and synchronizing regulations with the EU's overarching digital sovereignty goals, the Commission is establishing the groundwork for a quantum ecosystem that fosters competitiveness while providing societal advantages in sectors like secure communications, sustainable energy, and advanced healthcare.

Although obstacles remain, like disjointed national strategies, restricted private funding and reliance on non-European equipment, the trajectory is becoming more evident. By means of extensive planning, transnational collaboration and infrastructure unification, the EU is establishing the groundwork for a self-sufficient and innovation-capable quantum ecosystem aimed at global competition and societal benefits.

2.3. National and regional initiatives

Although the European Union directs comprehensive quantum policy via multi-year frameworks and key initiatives, the realisation and acceleration of quantum innovation frequently occur at the national and regional levels. Member states have initiated independent projects that embody their unique scientific traditions, industrial strengths and strategic goals. These initiatives enhance EU-level activities but also create a certain level of fragmentation regarding technology priorities, funding approaches and governance frameworks (European Commission, Quantum Europe Strategy, 2025).

Table 2.1 and 2.2 offer a comparative summary of key aspects of chosen national initiatives, whereas the following subsections examine each instance more thoroughly.

Country	Budget
United Kingdom (non-EU)	£ 3.5B ~ € 4.1B
Germany	€ 3B
France	€ 1.8B
Spain	€ 808M
Netherlands	€ 615M
Finland	~ € 500M
Italy	~ €500M
Austria	€ 107M
Sweden	~ € 100M
Switzerland (non-EU)	CHF 82.1M ~ € 85M
Norway (non-EU)	~ € 70M
Poland	€ 60M
Denmark	~ DKK 200M ~ € 27M

Table 2.1.: Country and investments

Country	Challenges
United Kingdom (non-EU)	Brexit limits alignment with EU, but global outreach compensates
Germany	Technology transfer gap, limited prototype scalability
France	Dependence on external chip production, fragmented hardware evaluation
Spain	Attracting private investment, coordinating regional infrastructures
Netherlands	Limited industrial uptake beyond ICT and telecom
Finland	Narrow domestic market, dependency on global demand
Italy	Fragmentation of initiatives, limited chip fabrication capacity
Austria	Translating research into commercial apps, EU alignment
Sweden	Scaling hardware prototypes, long-term funding continuity
Switzerland (non-EU)	Small market, reliance on international cooperation
Norway (non-EU)	Limited domestic hardware capacity, reliance on international R&D partnerships
Poland	Limited HPC focus, fragmented funding
Denmark	Limited large-scale industrial adoption

Table 2.2.: Country and challenges

Utilizing information gathered from authorized sources, the subsequent sections present an analysis of every national program, organized in decreasing order of funding. The summary also features nations that are outside the European Union yet continue to be significant to the European quantum ecosystem. This framework emphasizes the impact of the strategies employed by countries with the biggest budgets on both their internal growth and the wider European environment

2.3.1. United Kingdom

Though the United Kingdom is out of the EU, it remains a significant player in the European quantum landscape. Launched in 2014, the UK National Quantum Technologies Programme (NQTP) has obtained over £1 billion in funding, with a further £2.5 billion pledged for the years 2024 to 2034. Its four Quantum Technology Hubs focus on communication, sensing, imaging, and computation. Companies like ORCA Computing, Riverlane and Quantinuum (a spin-off of Honeywell) are essential for industrial progress. Following Brexit, UK organisations remain involved in Horizon Europe and collaborate with EU counterparts via bilateral agreements (UKRI, 2025). Additionally, the UK government has emphasised quantum technologies within its National Quantum Strategy, released in 2023, which outlines specific objectives for developing a fault-tolerant quantum computer by 2035 and enhancing national resilience in quantum communications and navigation. The British Standards Institution (BSI) is additionally aiding global initiatives to standardise quantum technologies. The UK is cultivating a robust commercial environment with assistance from Catapult centres, Compound Semiconductor Applications Catapult and Digital Catapult, providing companies access to testbeds, regulatory advice and initial investment. Importantly, the government-supported “Quantum Catalyst Fund” and

Innovate UK initiatives aim to assist SMEs in converting research into scalable solutions, especially in healthcare, finance and aerospace.

Globally, the UK has established quantum cooperation pacts with nations such as the US, Canada and Japan, enhancing its status as a worldwide centre for quantum innovation. This twofold approach, strong integration with European research and autonomous global partnerships, allows the UK to serve as a link between the EU and broader international quantum networks.

2.3.2. Germany

Germany ranks among the leaders in national investment in quantum technology, thanks to the German government, which allocated more than €3 billion for quantum research and industrial applications via the Quantum Technologies Programme (QT.DE). Collaborative efforts among Fraunhofer Institutes, the German Aerospace Center (DLR) and companies like Siemens and Bosch seek to develop a national quantum ecosystem centred on scalable computing systems and quantum sensing (Federal Ministry of Education and Research, 2024).

Germany is home to a EuroQCS quantum computer positioned alongside an HPC facility in Jülich and it also backs various regional centres of excellence, particularly Quantum Valley Lower Saxony (QVLS), a collaboration involving TU Braunschweig, PTB, the Germany's national metrology institute, and DLR, the German Aerospace Center, aimed at developing ion-trap quantum computers featuring scalable architectures.

The Jülich Research Centre manages the UNIQORN project, which aims to integrate quantum processing units with HPC clusters for improved scientific simulation. From an educational perspective, the Quantum Future Programme of BMBF finances doctoral positions and startup support, whereas institutions such as TU Munich and LMU Munich have implemented interdisciplinary quantum programs.

In the industrial sector, Bosch has invested in quantum sensors for self-driving technology, while Siemens Healthineers is investigating quantum-boosted imaging. Even with this ecosystem, stakeholders emphasise the challenge of connecting prototypes to scalable platforms, stressing the necessity for more robust tech-transfer pathways.

2.3.3. France

In 2021, France started implementing its Quantum Plan, with a budget of €1.8 billion, focusing on quantum computing, post-quantum cryptography and quantum sensors. The project is overseen by CEA, INRIA, and Bpifrance, with backing from research institutions such as CNRS and companies like Pasqal and Quandela (EE Times Europe, 2021). Recent growth in 2025 encompasses additional funding in photonic computing and quantum interconnects, solidifying France's position in the EuroQCI rollout (Government of France, 2025).

The Paris-Saclay Quantum Cluster strengthens France's position, linking renowned institutions such as CNRS, ENS and Université Paris-Saclay with startups and corporations. The Plan Quantique finances extensive industrial partnerships, such as the collaboration between Quandela, which specialises in photonic quantum computing, and Pasqal, which is centred on neutral-atom processors. In 2025, each company revealed new collaborations with EDF and Airbus to investigate quantum simulation for optimising energy grids and discovering materials. France holds a strategic position in the EuroQCI initiative, providing quantum satellite prototypes through CNES and Ariane Group. Public funding is enhanced by Bpifrance's deep-tech investments, whereas GENCI facilitates access to national quantum simulators provided by Atos. Despite its systemic advantages, experts highlight difficulties in national chip production and uniform evaluation for quantum hardware.

2.3.4. Spain

Spain has recently solidified its status in quantum research with the National Quantum Technologies Strategy 2025–2030, which designates €808 million to enhance scientific leadership and promote industrial adoption (The Government of Spain launches Spain's first Quantum Technologies Strategy with an investment of €800 million, 2025). The project develops from the Quantum Spain initiative, managed by the Barcelona Supercomputing Center (BSC) and connected to the national supercomputing network (RES). It emphasizes the creation of local quantum hardware, photonics-driven solutions and secure quantum communication. Spanish research institutions such as CSIC and ICFO play a central role, complemented by startups like Qilimanjaro and Multiverse Computing that specialise in quantum software and optimisation for finance and logistics.

Spain also participates in EuroQCS by hosting one of Europe's quantum nodes. Despite these efforts, stakeholders point to limited private investment and fragmented regional initiatives, which may hinder the scalability of industrial applications without stronger coordination mechanisms (General Secretariat, 2025) .

2.3.5. Netherlands

The Netherlands remains at the forefront of quantum networking and hybrid platforms. Quantum Delta NL, supported by a €615 million investment from the National Growth Fund, is organised into three main hubs: Amsterdam, Delft and Eindhoven. The project focuses on creating a countrywide framework, promoting startup support and unifying education in quantum engineering (Quantum Delta NL, 2023). The initiative is led by QuTech, a partnership between TU Delft and TNO, which directs the Quantum Internet Alliance project and drives advancements in quantum communication protocols and long-distance entanglement distribution. The Dutch government supports a national quantum testbed for QKD and quantum-safe networking, featuring active nodes connecting Delft and Amsterdam. Numerous high-potential startups like Qblox, QuantWare and Delft Circuits play a role in an expanding hardware cluster closely associated with industry leaders such as ASML and Philips.

Educational initiatives encompass the establishment of a Quantum Career Hub and nationwide MOOC courses focused on quantum engineering. Despite its achievements, stakeholders have observed a difficulty in converting research excellence into widespread industrial impact, especially outside the ICT and telecom fields.

2.3.6. Finland

Finland has become a significant hub for superconducting technology, supported by companies such as IQM, academic institutions (Aalto University) and national research entities (VTT). Finland's strategic goals encompass integrating its hardware with EuroQCS and promoting export-focused initiatives for cryogenic electronics and control systems.

In early 2025, IQM launched a 20-qubit quantum processor as part of the EuroHPC infrastructure (IQM Quantum Computers, 2024). Along with the launch of quantum processors, Finland is also significantly involved in creating scalable quantum computing ecosystems by participating in European initiatives like the European Quantum Flagship and EuroQCI. The Finnish Quantum Institute, a partnership between Aalto University, the University of Helsinki and VTT, has a pivotal coordinating function in national quantum research and education. Additionally, public funding channels like Business Finland and the Academy of Finland have played a crucial role in promoting innovation within quantum technologies, with particular initiatives focused on quantum software, cryogenic control systems and hybrid classical-quantum computing architectures.

From an industrial standpoint, Finland is establishing itself as a centre for the production and evaluation of low-temperature electronics, with firms such as Bluefors offering crucial infrastructure for global quantum experiments. This collaboration of academic prowess, industrial strength and strategic alignment with EU priorities positions Finland at the leading edge of Europe's developing quantum technology scene.

2.3.7. Italy

In Italy, quantum research and development have expanded through national initiatives linked to the PNRR, National Recovery and Resilience Plan. Considerable funding has been channelled through initiatives such as "Extended Partnerships" (RESTART, NQSTI) and "Ecosystems of Innovation". The main institutions include INRIM and CNR, concentrating on metrology, hardware calibration and quantum algorithms. Italy is an acknowledged EuroQCS site and participates in the EuroQHPC Integration pilot project. Moreover, the National Quantum Science and Technology Institute (NQSTI), located in Florence, acts as an essential hub for managing quantum projects among over 50 Italian organisations and companies. The institute emphasises enhancing basic research, encouraging skills growth and advancing technology transfer between universities and industries. In this context, novel quantum computing testbeds and hybrid cloud infrastructures are being created, following EuroHPC objectives. Among these, CINECA holds a pivotal position as Italy's high-performance computing centre, housing one of the EuroQCS quantum nodes. It facilitates the incorporation of quantum processors into traditional HPC settings, providing expandable infrastructure for algorithm creation, hybrid simulations and access for industries.

Italy is also actively involved in developing quantum communication infrastructure through the EuroQCI initiative, with Leonardo and Telsy spearheading private sector efforts. Public-private partnerships are being increasingly encouraged to close the divide between research and implementation, especially in areas such as cybersecurity, quantum sensing and space-oriented applications. These national initiatives align with Italy's larger goal to be a key player in Europe's agenda for digital and technological sovereignty.

2.3.8. Austria

Austria initiated its Quantum Austria initiative (2021–2026), backed by €107 million from the Recovery and Resilience Facility, to promote national excellence in quantum computing, sensing and communication (Quantum Austria, 2024). The program is managed by the Austrian Research Promotion Agency (FFG) and the Austrian Science Fund (FWF), aiding both basic research and practical initiatives. The University of Innsbruck, famous for ion-trap quantum computing and the Austrian Institute of Technology (AIT) lead the way. Austria is also significant in EuroQCI via the QCI-CAT project, which seeks to establish secure national quantum communication systems. Nonetheless, converting academic advancements into commercially viable products is still a challenge and the lack of industrial involvement highlights the necessity for stronger alignment with EU-level initiatives (Austria E. of., 2025) .

2.3.9. Sweden

Sweden is becoming a hub for superconducting quantum technology due to efforts led by Vinnova and RISE (Vinnova finances a Swedish platform for quantum technology, 2023). The Wallenberg Centre for Quantum Technology (WACQT) at Chalmers University spearheads national initiatives aiming to develop a 100-qubit superconducting quantum computer in the next ten years. Sweden has invested in quantum simulation and education, collaborating with Ericsson and hardware startups like SCALINQ. In spite of robust academic leadership and governmental backing (€100 million), obstacles persist in maintaining long-term funding and establishing a clear route to industrial application, as the majority of initiatives are still focused on research (Ernström, 2025) .

2.3.10. Switzerland (non-EU)

Even though Switzerland is not part of the EU, it plays a significant role in Europe's quantum ecosystem. The Swiss Quantum Initiative (SQI), overseen by the Swiss Academy of Sciences, allocated a budget of CHF 82.1 million for the period from 2025 to 2028 (SwissQuantum, 2025). It leverages Switzerland's extensive experience in quantum communication and cryptography, spearheaded by organizations such as

ETH Zurich, EPFL and firms like ID Quantique. Funding programs such as the BRIDGE Quantum Call 2025 promote initial-stage innovation and partnerships between universities and startups (BRIDGE Quantum call for projects 2025, 2025) . Switzerland has established itself as a centre for QKD technologies and secure communication networks, working closely with EU projects even though it is not a member. Nonetheless, the limited domestic market and significant dependence on global partnerships present structural obstacles for increasing industrial adoption.

2.3.11. Norway (non-EU)

Norway, while not part of the EU, is involved in Horizon Europe and allocates funding to specialized areas of quantum research, especially in software and energy applications. The Research Council of Norway has committed around €70 million to quantum projects, aiding organizations like NTNU, Simula Research Laboratory and the University of Oslo (Abdel-Kareem, 2025). Industrial partnerships involve initiatives with Equinor to investigate quantum optimization for energy systems and logistics. Companies such as Arqit Norway are involved in quantum cryptography and QKD. Still, Norway’s internal ecosystem is small, with restricted hardware development capabilities, rendering global collaborations vital for advancement (Harnessing our quantum potential – towards a Norwegian quantum strategy, 2025) .

2.3.12. Poland

Poland has focused its quantum initiatives on communication and sensing, tightly linked to its involvement in EuroQCI. With backing from the National Science Centre and EU structural funds, Poland has allocated approximately €60 million to develop national capacities. Entities like the University of Warsaw and NASK have created QKD testbeds, whereas firms such as Creotech Instruments are providing quantum hardware parts. Though Poland is essential in secure communication initiatives, the national landscape encounters disjointed funding and a narrow emphasis on quantum computing, necessitating collaboration with European consortia for future competitiveness.

2.3.13. Denmark

Denmark merges its robust heritage in quantum physics, spearheaded by the Niels Bohr Institute, with new industrial initiatives in quantum photonics. Launched in 2023, the National Quantum Strategy, backed by DKK 200 million, aims to enhance national research capabilities and connect Denmark to European initiatives like EuroQCI. Sparrow Quantum and startups focused on quantum light sources showcase Denmark's expertise in photonics and quantum internet technologies (Government, 2023) . Nevertheless, the ecosystem continues to face challenges with constrained industrial scaling, since large-scale development of quantum hardware is not yet a focus (Brixen, 2025).

Collectively, these national and regional efforts underscore both the diversity and intricacy of Europe's quantum environment. Large economies like Germany, France, and the United Kingdom are leading the agenda with multi-billion-euro investments and strong industrial collaborations, while mid-sized nations such as the Netherlands, Finland, Italy, and Spain are establishing niches in fields like superconducting qubits, hybrid HPC integration, and photonics. Lesser-known nations such as Austria, Denmark, Sweden, Norway, Poland, and Switzerland serve a supportive function by focusing on quantum communication, sensing, or specific hardware advancements.

In spite of this variety, numerous structural patterns arise. Almost all initiatives highlight the importance of linking academic achievement with industrial application, but numerous nations continue to encounter a "valley of death" separating prototypes from scalable platforms. Secondly, although Europe as a whole shows substantial scientific capability, the division in funding priorities, governance structures, and industrial ecosystems hampers critical mass and slows down commercialization. Ultimately, non-EU nations like the United Kingdom, Switzerland and Norway maintain strong connections with EU research networks, highlighting the transnational aspect of quantum innovation while also prompting discussions regarding long-term strategic independence.

In general, the national strategies enhance and support the broader quantum agenda of the EU, while also revealing deficiencies in coordination and the distribution of resources. Guaranteeing interoperability, preventing redundancy and encouraging common standards will be crucial for Europe to convert its disjointed efforts into a unified, globally competitive quantum ecosystem.

Even with the national momentum, interviews carried out for this thesis uncovered a widely expressed worry: the danger of excessive fragmentation. One interviewee remarked, “Europe has established numerous strong hubs, yet it still doesn't have enough critical mass to compete on a global level.” Some highlighted differing standards, overlapping initiatives and minimal alignment among Member States. A senior ecosystem analyst noted, “Europe has an abundance of nodes, yet remains deficient in cohesive networks.” To challenge this, increased coordination between national strategies and EU-wide plans will be crucial. Collaborative governance, common standards and improved public-private partnerships can boost the unity, scalability and global competitiveness of Europe's quantum ecosystem.

2.4. Mapping European key players

The European quantum ecosystem comprises a central group of key players whose influence extends beyond national borders and shapes the direction of technological, industrial and political advancements. These participants operate at various levels of the value chain, spanning from foundational research to commercialisation and serve as essential facilitators for Europe's goal of achieving quantum technological independence. In contrast to the previously mentioned national and regional programs, this section centres on the individuals who propel the system, the nature of their impact and their alignment with European priorities.

European research institutions like QuTech (Netherlands), CEA and CNRS (France), Aalto University and VTT (Finland), INRIM and CNR (Italy), PTB and DLR (Germany) serve not only as contributors to scientific output but also as pivotal hubs in the knowledge network. These organisations frequently engage in and head consortia within the Quantum Flagship, Horizon Europe and EuroQCS, establishing research priorities and technical specifications. Their strategic importance is in maintaining long-term infrastructure, cultivating future talent and acting as reliable intermediaries between policy and industry. These participants are vital for the ongoing knowledge development in Europe and for creating a scientific credibility that holds its ground against American and Chinese institutions.

The McKinsey Quantum Technology Report states that European startups are increasingly setting themselves apart by aiming for application-specific platforms and emphasising hardware-software co-design, instead of directly contesting with US and Chinese companies in the pursuit of general-purpose quantum dominance. (McKinsey, 2025)

A cluster of highly specialised companies within Europe’s quantum computing ecosystem is essential for creating and providing the fundamental components, control systems, and infrastructure needed to construct scalable quantum computing platforms. These companies, while varied in their technological emphasis, from quantum processors and control systems to cryogenic technologies and quantum software frameworks, together constitute the industrial foundation that allows Europe to seek technological independence and engage competitively in the rising quantum market.
Prominent in this field are:
IQM (Finland)
IQM has positioned itself as Europe's leading startup in superconducting quantum processors, concentrating on bespoke, on-site quantum computers designed for specific sector applications (IQM, 2025) . Instead of embracing a cloud-first approach, IQM works closely with HPC centres and industry partners to implement quantum systems tailored for areas such as materials science, quantum chemistry, and AI-enhanced simulations. The company’s approach aligns with Europe’s strategic requirement for sovereign infrastructure implementation and addresses the continent’s focus on performance driven by applications rather than just qubit numbers. IQM is heavily engaged in co-design initiatives alongside LUMI-Q and contributes to educational efforts through InstituteQ (Danish e-Infrastructure Consortium, 2024).
Pasqal (France)
Pasqal is a leading European company in neutral-atom quantum computing. In contrast to gate-based methods, Pasqal’s hybrid systems that combine analogue and digital elements are crafted to address particular industrial challenges in energy optimisation, aerospace and advanced materials (Pasqal, 2025). Their approach emphasises industry-focused pilot initiatives, created in partnership with major companies like EDF and Airbus, enabling them to establish early commercial positions. The McKinsey report highlights Pasqal’s strategy as a model of vertical specialisation, placing Europe in application niches where a global quantum advantage can be achieved more quickly (The Quantum Insider, 2024).

Quandela (France)

Quandela operates at the intersection of quantum computing and photonics, developing reliable single-photon sources and optical processors. In contrast to numerous hardware rivals, Quandela offers cloud access to photonic quantum computing systems, allowing broader availability for developers and researchers (Quandela, 2025) . Their photonic chips serve as a key resource for secure quantum communication (QKD), positioning Quandela as significant in both computation and cybersecurity (Quantum Computing Report, 2024). Partnerships with GENCI and participation in EuroQCI strengthen their role as a vital contributor to Europe's quantum infrastructure initiative.

ORCA Computing (UK)

ORCA Computing is leading the way in modular, fibre-integrated quantum processors that utilize photonic technologies for scalable, quantum computing solutions at room temperature. Their design caters to distributed quantum computing frameworks, facilitating the integration of quantum accelerators into current classical data centre settings (ORCA, 2024). ORCA's collaborations with defence entities and telecom providers establish it as a key facilitator of secure, adaptable quantum computing implementations within hybrid cloud environments (DataCenterDynamics, 2024). This corresponds with Europe's emphasis on interoperability and sovereign cloud access.

Riverlane (UK)

Riverlane is a prominent European player in the quantum software domain, creating Deltaflow.OS, an operating system aimed at uniting hardware diversity and facilitating hardware-agnostic quantum computing (Riverlane, Riverlane , The Operating System for Quantum Computers, 2025). Riverlane’s efforts are essential for Europe's plan to promote a unified and interoperable quantum ecosystem, enabling applications to shift effortlessly among various hardware platforms. Their collaborations with various hardware vendors throughout Europe guarantee that they are establishing the benchmarks for middleware and software-stack integration. McKinsey recognises Riverlane as a key contributor to simplifying the intricacies of hybrid quantum-classical processes (Riverlane, Quantum Error Correction Report 2024, 2024).

Qblox (Netherlands)

Qblox focuses on modular control stack hardware for quantum computing, providing scalable control systems that can be utilised across various quantum platforms, including superconducting qubits and ion-trap setups (Qblox, 2025). Their systems are essential for ensuring real-time control and error reduction, a limiting factor in the scalability of current quantum hardware. Qblox simplifies standardisation across Europe's diverse hardware landscape by offering "plug-and-play" control solutions, aiding emerging startups and research labs in prototyping quantum systems more efficiently (Alliance, 2024).

QuantWare (Netherlands)

QuantWare tackles a major strategic gap in Europe: the scalable, local production of quantum processors (QuantumWare, 2025). Their "foundry-as-a-service" approach enables research institutions and startups to request custom-designed superconducting quantum chips in small and medium quantities, offering a flexible and affordable option compared to foreign foundries. This strategy is crucial for Europe's initiatives to establish a decentralised, independent supply chain for quantum hardware manufacturing. QuantWare's focus on modularity and interoperability bolsters Europe's vision of a versatile, application-oriented quantum hardware ecosystem.

Bluefors (Finland)

Bluefors is a worldwide frontrunner in dilution refrigeration systems, essential for the functioning of superconducting qubits. By preserving leadership in this essential aspect of the quantum hardware stack, Bluefors guarantees that Europe maintains control over a crucial segment of the quantum computing framework. Their goods are utilised globally, yet their strategic significance for Europe is in ensuring cryogenic supply chains within the EU, minimising dependence on outside suppliers and enhancing Europe's strength in hardware implementation.

Oxford Instruments (UK)

Oxford Instruments enhances Europe's infrastructure capabilities with its precision measurement instruments and cryogenic technologies, facilitating both R&D and large-scale applications of quantum systems. Their partnership with quantum startups and involvement in national projects establish Oxford Instruments as a crucial facilitator in expanding quantum hardware platforms, particularly in testing and validation settings.

These firms perform a system-building function, providing crucial hardware and software that support quantum system integration. Their significance extends beyond innovation, they also embody essential components of the supply chain that Europe must maintain internally to ensure its technological independence.

Additionally, by drawing in investments and forming collaborations with international entities (e.g., Airbus, EDF, Bosch, IBM), they act as business links connecting the European ecosystem and global markets. EU policymakers monitor their growth paths closely as signs of Europe's ability to translate quantum innovation into industrial competitiveness.

A unique set of entities acts as infrastructure providers, organisations that manage or utilise the computing and communication platforms that support the quantum ecosystem. These comprise:

- EuroHPC JU and national HPC centres (Jülich, GENCI, CINECA)
- Leonardo (Italy) and Thales Alenia Space (France) for the EuroQCI space segment
- Atos for emulators and simulation platforms
- Catapult centres (UK) for SME access and testbeds.

These players are essential as they guarantee accessibility, scalability and sovereignty. The choices they make regarding infrastructure, such as the platforms for hosting and the distribution of computing resources, directly impact which technologies grow and which research communities flourish.
They also contribute to standardisation, procurement and interoperability, aligning with EU-level objectives such as the Quantum Competence Framework and the Digital Decade goals.

At the strategic level, entities such as QuIC (Quantum Industry Consortium), ETSI and national innovation bodies like Bpifrance, Innovate UK and Business Finland act as integrators of ecosystems. They don't create technology themselves but convert EU-wide objectives into national funding programs and investment instruments, facilitate collaborations across sectors and borders and promote SME involvement, standards and consistency in policy.
QuIC has specifically become a key player in promoting a unified industry perspective across Europe, engaging in policy discussions, aligning industry contributions to Quantum Flagship working groups and influencing regulations on certification and procurement.

Identifying the crucial participants in the European quantum ecosystem uncovers a web of distinct yet interconnected roles. The difficulty for the EU lies not only in financing or organising these entities but also in guaranteeing that they operate as a unified, mutually supportive framework. The global competitiveness of Europe in quantum technologies hinges on its ability to align its research institutions, industry leaders, infrastructure providers and policy makers into a cohesive strategic framework that can sustain long-term technological leadership. These infrastructure suppliers are crucial for sustaining technological autonomy from non-European providers. For example, Bluefors cryogenic systems are utilised worldwide, decreasing dependence on American or Asian supply chains for quantum hardware testing and functioning. Likewise, GENCI and CINECA provide essential simulation and benchmarking settings that are vital for algorithm creation, particularly for startups without internal computational resources.
Standardisation and interoperability initiatives signify another dimension of strategic influence. Entities such as the European Telecommunications Standards Institute (ETSI) and the British Standards Institution (BSI) are engaged in establishing standardised protocols for quantum communication, post-quantum cryptography and hybrid quantum-classical cloud systems. Simultaneously, extensive consortia and international collaborations are developing as key tools for integration. The Quantum Internet Alliance, spearheaded by QuTech and featuring collaborators from Germany, Italy, Spain, and Austria, is advancing long-range entanglement protocols. Likewise, the EuroQHPC-Integration initiative is enabling common middleware, APIs, and cloud interfaces across national quantum computers.

Additionally, the rise of 'hybrid actors', entities that occupy various roles, introduces further complexity and strength. For instance, IQM is not merely a hardware manufacturer; it also partners with research organisations and national governments to jointly create educational initiatives and integrate systems. Similarly, Pasqal has played a crucial role in hardware development as well as in application-specific pilot initiatives within the energy and aeronautics sectors.
In the end, Europe's competitiveness in the global quantum race will hinge not solely on scientific advancements or prominent investments but on its ability to foster a unified, compatible, and strategically independent ecosystem. Crucial actors need to keep broadening their roles: research institutions should accelerate industrialisation,

businesses must aid in standardisation and regulatory bodies must enhance alignment processes.

The primary categories of European quantum actors are outlined in the table below, along with illustrative examples, their strategic roles along the value chain, and the main risks that could impede scale-up.

Category	**Players**	**Strategic role**	**Main risk**
Research	QuTech; CEA/CNRS; VTT/Aalto; PTB/DLR; CNR/INRIM	Create a talent pipeline, set a scientific roadmap, and oversee EU partnerships.	Slow tech transfer and dispersed work
Hardware	IQM; Pasqal; Quandela; ORCA	Allow for vertical use cases and co-design between HW and SW	Dependency on the foundry; vendor lock-in
Control	Qblox; Bluefors; Oxford Instruments	Systems for stability and scalability	CAPEX/OPEX supply bottlenecks
Software	Riverlane (Deltaflow); open toolchains	Interoperability, orchestration of hybrid HPC+QC	Industrial adoption of heterogeneous APIs
Infrastructures	EuroHPC/EuroQCS; LUMI-Q; GENCI; CINECA; Quantum Inspire; Atos QLM	Hybrid workflows and sovereign access	Interoperability across vendors; OPEX
Ecosystem	Early adopters (Airbus, EDF, Bosch);	Align industry and policy; establish	Uncertain ROI signals and voluntary uptake

	QuIC; ETSI; Bpifrance; Innovate UK; Business Finland	markets and standards	

Table 2.3.: European key players, categories, strategic roles and main risks

2.5. Infrastructures and platforms for quantum computing access

The European Union has emphasised the establishment of accessible and independent quantum infrastructures as a vital facilitator for its strategic goals in quantum computing. This initiative aims to promote scientific leadership and to ensure equitable access to quantum technologies for research institutions, SMEs and industry players throughout member states.

Infrastructural capacity is regarded as a key element of Europe's competitiveness on a global scale, minimising reliance on non-EU technologies and promoting innovation that aligns with European values and market demands (European Commission, 2025).

Numerous quantum cloud platforms have been created throughout Europe to facilitate broad, easy access to quantum resources. These infrastructures are designed to simulate, emulate, and, when feasible, run quantum algorithms on physical or hybrid systems.

It is useful to highlight the Atos Quantum Learning Machine (QLM), an advanced simulator that replicates quantum logic operations on conventional hardware. It is frequently employed for educational purposes, algorithm creation and benchmarking activities by users in academia and industry.

The QLM is essential for connecting quantum software development with the limited availability of physical quantum processors, especially in early-stage projects that lack stable hardware. It has been accepted by various European research centres and HPC organisations, such as GENCI in France and CINECA in Italy, as an additional resource for hybrid workflows and algorithm development.

From a strategic perspective, the QLM aids Europe's wider objective to promote algorithmic preparedness and quantum programming capabilities, particularly within academic and SME settings where access to genuine quantum hardware is still restricted or too expensive. Even with its high fidelity and modular design, the QLM does not accurately replicate quantum noise or decoherence at the hardware level and thus cannot entirely replace physical testbeds when creating fault-tolerant protocols or hardware-aware optimisations. Still, its scalability, predictable results and compatibility with Qiskit, Cirq and exclusive SDKs render it an essential part of the European quantum computing landscape

In the Netherlands, Quantum Inspire, created by QuTech and TNO, offers one of the limited publicly accessible cloud platforms in Europe for real quantum hardware, providing superconducting and spin-qubit processors to researchers and developers. It has played a crucial role in promoting open science and reproducible outcomes, consistent with EU goals for transparency and accessibility (QuTech, 2025).
Furthermore, Europe has started incorporating quantum computing into its high-performance computing (HPC) framework. The LUMI-Q addition to the Finnish LUMI supercomputer is a significant advancement for hybrid classical-quantum tasks. LUMI-Q acts as a platform for managing quantum acceleration activities in climate modelling, molecular dynamics and financial simulations (EuroHPC JU, 2025).
The EuroQCS initiative, directed by the EuroHPC Joint Undertaking, aims to implement a minimum of six quantum computing systems in Poland, Italy, Germany, France, Spain and the Czech Republic. These systems are designed to function in close collaboration with local HPC centres, providing hybrid functionalities and unified cloud-based accessibility.
Every centre is being outfitted with distinct quantum processors, covering superconducting to ion-trap designs and is expected to create explicit access policies, training programs and technical assistance services (EuroHPC JU, 2025).
Access models differ between platforms and nations, yet the tendency is toward inclusive and scalable systems. For example, Quantum Inspire provides open access through account-based logins and tutorials, whereas EuroHPC facilities implement a tiered approach that includes peer-reviewed proposals, subsidised access for SMEs and commercial choices for businesses. National quantum nodes are urged to share usage statistics and uphold publicly accessible roadmaps to promote transparency and accountability (Digital Europe Programme, 2025). A key goal of Europe's infrastructure plan is the unification of quantum and classical computing (HPC+QC).

Multiple initial test scenarios have demonstrated promise: quantum annealers and simulators are employed in logistics for optimisation processes, whereas hybrid algorithms such as VQE are being experimented with in chemical simulations. Such integrations frequently depend on orchestrators to arrange quantum and classical tasks according to resource needs, error limits and data proximity (QuIC, 2025).

A significant limitation in Europe's quantum infrastructure approach is the absence of a sovereign and scalable fabrication ecosystem for quantum processors. Although research institutes and startups in Europe have advanced significantly in crafting superconducting and atom-based architectures, the production of processors, particularly on a large scale, still heavily relies on foundries outside the EU, frequently situated in the United States or East Asia. This reliance creates a strategic risk, particularly during periods of geopolitical conflict or supply chain issues, but also restricts Europe's capability to innovate, refine and transition designs efficiently from research to market.
This disparity is even more significant when contrasted with other international rivals. In the United States, firms like IBM, Google, Intel, and Rigetti take advantage of direct access to local semiconductor foundries that facilitate quick prototyping and expansion. In the same way, China has merged its quantum research initiatives with substantial government-supported investments in semiconductor production, targeting a complete supply chain that minimizes reliance on foreign sources. Europe, on the other hand, has top-tier research institutions and innovative startups (e.g., Pasqal, Quandela, IQM, AQT) but struggles to convert lab results into commercial-grade processors without relying on external partners for production. This scenario not only hinders the speed of innovation but also puts European firms at risk of intellectual property loss and dependency issues.

The lack of a specialized quantum foundry further expands what might be termed a new "hardware valley of death": although European startups may reach encouraging outcomes with prototypes, their capability to transition to commercially viable hardware is constrained by production bottlenecks. This structural vulnerability threatens to diminish the effectiveness of well-funded programs like EuroQCS or Qu-Pilot, as access platforms and cloud integration ultimately rely on hardware that Europe is not yet capable of producing on its own.

From a strategic policy viewpoint, the absence of fabrication sovereignty poses a direct challenge to Europe’s ambition of attaining digital and technological independence. It generates a contradiction in which Europe can spearhead the establishment of quantum access models, hybrid HPC integration, and algorithm creation, yet still relies on outside entities for the essential component of the value chain—the processor. If this bottleneck is not addressed, the long-term competitiveness of the European quantum ecosystem will stay at risk

Consequently, recent strategic talks among the European Commission, QuIC and national agencies have proposed the creation of a European Quantum Foundry Initiative (EQFI). This facility would reflect the approach of the European Chips Act by integrating public financing with industrial co-investment to develop a dedicated fabrication infrastructure designed for quantum computing. Initial proposals propose a decentralised foundry system that merges various national strengths into a cohesive supply chain.
The possible advantages of this initiative are many: technological independence, quicker innovation cycles, standardised processes and more defined commercialisation routes for European hardware startups. Nonetheless, obstacles persist, such as considerable capital investment, extended construction periods and the technological variation among quantum platforms. The variety of quantum computing approaches, superconducting, photonic, ion trap and neutral atom, brings up questions regarding which platforms should be emphasised for large-scale production. A cohesive European strategy on quantum hardware would be crucial to direct these choices and prevent technological disunity.

Various hybrid models have been suggested, including open-access micro foundries situated alongside national HPC and quantum facilities, enabling SMEs and researchers to produce small-batch chips with modular PDKs. This method is consistent with the essence of open innovation and collaborative infrastructure championed by initiatives such as EuroQCS and Qu-Pilot. Skill will also be an essential facilitator. Running a quantum foundry demands engineers with expertise in cryo-CMOS integration, vacuum packaging and nanoscale fabrication. Collaborative funding for quantum engineering education initiatives will be essential to develop a lasting European workforce.

Interviewed experts for this thesis highlighted that "just having quantum access is insufficient; we must have the ability to utilise it strategically." This sentiment indicates a wider worry that, without concurrent investment in algorithm creation, skills development and integration tailored to specific applications, infrastructure risks may be inadequately leveraged. Specifically, there is a demand for more vertically integrated software stacks that enable businesses to evaluate quantum tools within their sector-specific processes, like in pharmaceutical research, traffic control, or financial risk assessment.

To address this, the Qu-Pilot and Qu-Test initiatives were launched under the Digital Europe Programme. These initiatives aim to benchmark quantum hardware, provide real-world testing environments and offer pre-commercial access to SMEs and industrial users. The associated Q-Access Framework, developed by QuIC in 2025, proposes a modular architecture for quantum cloud services, covering everything from authentication and scheduling to telemetry and application orchestration. This is seen as a critical move toward a unified European quantum access layer (QuIC, 2025).

The European approach to quantum computing infrastructure development is both ambitious and inclusive. By investing in sovereign, cloud-based quantum systems and integrating them into its world-class HPC ecosystem, Europe is laying the groundwork for scalable, interoperable and application-driven quantum computing. However, realising the full potential of these infrastructures will require overcoming persistent technical, organisational and educational challenges, especially as the quantum computing landscape matures.

2.6. Positioning of the European quantum cluster in a global context: a comparative analysis with the US and China

Building on Section 2.1's global overview, this section quantifies the differences and distils implications for EU strategy. In the rapidly changing international competition for quantum supremacy and technological independence, the European Union faces two major centres of quantum innovation: the United States and China. Every actor represents a unique strategy for funding, utilising and managing quantum technologies. To have a comprehensive examination of Europe's relative standing, it is opportune to focus on five key aspects: investment amounts, supply chain independence, innovation frameworks, patent development and strategic coherence.

In terms of investment gaps and strategic dedication, Europe has made considerable progress in unifying public funding for quantum research, with more than €7 billion allocated through the Quantum Flagship, Horizon Europe, Digital Europe and various national plans (European Commission, 2025). However, it still lags structurally behind the United States and China in absolute figures and the proportion of public-private co-financing. The U.S. quantum landscape thrives due to flexible funding options for startups, supported by federal agencies like DARPA, NSF and DOE, which have pledged more than $15 billion in capital (Council National Science and Technology, 2024).

China's approach, driven by strategic central planning and the Ministry of Science and Technology, has invested over $15 billion, prioritising state-owned infrastructure, national defence and leadership in quantum communications (Groenewgen, 2024)

Regarding technological independence and supply chain vulnerability, a significant weakness for Europe is its reliance on non-European supply chains for essential quantum components. These consist of dilution refrigerators, packaging for photonics, cryogenic electronic systems and control circuits. The US possesses the industrial capability for complete vertical integration, China has nationalised its semiconductor foundry capacity, whereas Europe depends on external suppliers or small, fragmented vendors, predominantly located in a limited number of Member States.

The framework of quantum innovation varies greatly among the three primary global regions, as some adopt collaborative approaches while others emphasise competitive tactics.

The United States promotes high-risk innovation via prestigious universities, robust VC investment and close connections between startups and national laboratories.

China employs a vertically integrated, state-managed system that encompasses national laboratories, military-associated organisations and an expanding domestic market for quantum-secured communications.

The European Union follows a joint public-private approach based on academic achievements and industry participation, driven by policy. Although Europe excels in publications and standardisation efforts, it frequently lacks the flexibility and willingness to take risks seen in American and Chinese entities. The transfer of innovation continues to be a constraint.

Trends in Intellectual Property and Patents Patent information aids in measuring technological advancement and prospective commercialisation. As reported by the European Patent Office and Lens.org (2025), the United States tops the list for granted patents in quantum technology, particularly in areas such as error correction, hardware design and hybrid algorithms.

China has swiftly accelerated its filings, especially in quantum key distribution (QKD), photonic chips and communication protocols. Europe's stance is more divided: although research output is significant, PCT submissions and industrial patent registrations are still relatively low. New companies such as IQM, Pasqal and Quandela are starting to alter this path, yet structural technological transfer constraints continue to hinder momentum.

Strategic insights from interviews with experts carried out during this research phase revealed multiple important viewpoints: "Europe excels in research but falls short in technology transfer and industrial leadership." For this reason, it is convenient to consider that by managing its strengths and tactical deficiencies, Europe's distinctive advantages are found in its unified governance, exceptional research capabilities and dedication to ethics and interoperability. Nonetheless, it encounters structural vulnerabilities in scaling technologies, drawing risk capital and ensuring technological sovereignty.

Interviews carried out in this research stage also revealed a consistent strategic insight: owing to Europe's late entry into quantum computing investments and its relative shortfall in private capital mobilisation, many experts contend that technological differentiation is a practical and essential route for Europe to attain a competitive position in the global quantum competition. Instead of engaging in a direct competition for qubit supremacy, where U.S. and Chinese entities are already established, Europe ought to capitalise on its scientific prowess to create alternative quantum computing frameworks and hybrid approaches, emphasising application-specific platforms, noise-resistant systems and vertical integration in areas like pharmaceuticals, climate modelling and quantum-secure cybersecurity.

This differentiation approach would enable Europe to leverage its advantages in system interoperability, open innovation environments and standards creation, establishing itself as a worldwide leader in quantum-classical hybrid computing and

specialised hardware for industry-specific applications. By emphasising sectors where agility, accuracy and specialised knowledge surpass sheer qubit numbers, Europe might create a distinct technological space, decreasing reliance on foreign supply chains while bolstering its strategic independence.
Experts also stressed that this route necessitates a concentrated effort on foundry capability, specialised processor design for applications and adaptable cloud-access structures, allowing European firms to adjust and respond more quickly to new industrial needs.

Although the United States leads in the startup and commercial scale-up process and China incorporates quantum into its national security framework, Europe needs to establish its competitive edge based on reliable supply chains, industrial independence and cross-border cooperation. To stay pertinent, the EU needs to focus on strategic procurement, create its own quantum foundries and manufacturing capabilities and ensure cohesion among Member States to prevent fragmentation. A greater focus on industry-ready applications, scaling ventures, and aligning policies will be crucial for turning scientific leadership into lasting economic and strategic benefits.

Chapter 3 Industrial applications and use cases

3.1. Cross-industry potential and transferability: absorptive capacity, innovation capability, cross-sectoral transferability

The industrial implementation of quantum computing cannot be examined only within the limits of specific sectors. As a general-purpose technology (GPT), its transformative ability spans various industries, producing cross-sector spillovers that can improve innovation outcomes and economic development. Grasping the processes of absorptive capacity, innovation capability and cross-industry transferability is crucial for evaluating the diffusion routes of quantum technologies.

Absorptive capacity, initially defined by Cohen and Levinthal, concerns to a company's capability to recognise, incorporate and utilise external information (Cohen & Levinthal, 1990). Recent research clarifies this definition by highlighting its dynamic and systemic characteristics. Other studies show that absorptive capacity has a major impact on innovation results, where organisational learning serves as a mediating element. This indicates that companies must have both access to external knowledge and internal mechanisms processes, culture and skills to convert that knowledge into real innovations (Sancho-Zamora, Hernández-Perlines, Peña-García, & Gutiérrez-Broncano, 2022).

In the same tone, other experts emphasise that dynamic absorptive capacity, the ability to consistently adjust knowledge acquisition and assimilation processes, has a strong correlation with enduring innovation performance. In advanced fields like quantum computing, where technological frameworks change quickly, this dynamic aspect becomes a vital factor in determining competitive advantage (Jiao, Du, Shi, Hou, & Gui, 2021) .

The second essential aspect, innovation capability, relates to the organisational skills and resources that allow companies to create and execute new products, services or processes. A study broadens this viewpoint to encompass digital and deep-tech realms, discovering that the ability to innovate is enhanced when coupled with robust absorptive capacity, especially within intricate value chains like those in quantum technology. Their study indicates that in areas with significant technological complexity, the incorporation of external knowledge necessitates sophisticated skills in systems engineering, interdisciplinary collaboration and market awareness (Abourokbah, Mashat, & Salam, 2023).

Within the European framework, the ability to innovate in quantum technologies relies on the strategic measures discussed in the prior chapter, yet its importance is evident when examining tangible results. Firms like Pasqal in France or Riverlane in the UK illustrate how academic breakthroughs can swiftly transition into industrial uses, while partnerships such as Quantum Valley Lower Saxony in Germany showcase the importance of local ecosystems in organising talents and facilities. Italy serves as a notable example: CINECA, a top HPC centre in Europe, is set to accommodate a EuroQCS quantum computer linked to the Leonardo supercomputer, showcasing how hybrid HPC–quantum setups enhance the continent's ability to absorb new technologies. These instances illustrate that Europe's innovative potential is rooted not just in scientific prowess, but also in coordinating stakeholders, leveraging resources and fostering cross-industry transfer avenues, all of which enhance competitiveness and technological independence.

The concept of cross-industry transferability emphasises how innovations created in one sector can be modified for application in different ones. This systematic review regarding cross-industry innovation, recognise three main mechanisms facilitating these transfers:

Analogy-driven transfer, in which solutions from one domain motivate problem-solving strategies in a different area

Transfer is reliant on technology, which includes the modification of technical elements or systems across various fields

Transfer through collaboration, where partnerships across sectors directly enable co-creation (Lavado, Fernandez, Vlaisavljevic, & Medina, 2023)

In quantum computing, this means that advancements in algorithms within one domain (e.g., quantum chemistry) could be applied to other areas (e.g., materials science or pharmaceuticals), as long as the target sector possesses the necessary absorptive capacity and innovation potential to incorporate these solutions. Kerstens also highlights that innovation intermediaries, including research and technology organisations (RTOs) and industry consortia, are crucial for improving absorptive capacity for digital innovation across industries, especially by fostering awareness capacities and coordinating knowledge exchange among multiple stakeholders (Kerstens & Langley, 2025) .

From a management viewpoint, the interaction among these three facets forms a strategic preparedness structure for new technologies. Companies that possess strong absorptive capacity and robust innovation skills are better positioned to effectively adapt quantum computing solutions created in different industries. In contrast, industries with restricted absorptive capacities might find it challenging to harness the benefits of quantum technologies, even if these can be technically shared.

Viewed through the lens of management, absorptive capacity, innovation capability, and transferability serve as both conceptual dimensions and catalysts for strategic decision-making. Companies must evaluate if they should regard investments in quantum as real options, weighing the expenses of early involvement against the possibility of obtaining a sustainable competitive edge. Strategic decisions involve whether to develop internal capabilities or depend on outside collaborations, how to place themselves within cooperative frameworks like local clusters or European partnerships, and how to address risks linked to technological underdevelopment. At the policy level, alignment with programs such as Horizon Europe or the Quantum Flagship offers funding avenues and access to knowledge networks, strengthening organisational readiness. Ultimately, decision-makers must assess quantum readiness not only from a technical perspective but also within a wider context of strategic options that include investment timing, resource distribution and ecosystem involvement.

3.2. Sectoral focus areas for quantum computing

Quantum computing is considered a versatile technology that could revolutionise various sectors by providing computational powers that exceed those of traditional systems. Its initial effect will be particular to specific sectors, appearing first in areas where computational complexity and combinatorial optimisation challenges are most intense and where the expenses of intractable issues are significant. Driven by existing R&D directions, pilot initiatives and discussions with experts, five industrial sectors emerge as initial adopters of quantum technologies.

While quantum computing is presented as a technology for general use, its adoption will vary across different sectors. Not all sectors are equally prepared or appropriate to harness value from quantum advancements in the near to mid-term.
Initially, infrastructural preparedness continues to be a restricting element, in fact, numerous industries are without hybrid quantum–classical testbeds or do not possess the specialised personnel required to incorporate quantum algorithms into their current workflows. The McKinsey Quantum Technology Monitor indicates that only a few sectors, finance, pharmaceuticals and advanced manufacturing, currently exhibit the ability to transform quantum research into initial business value. Other sectors, like conventional retail or low-margin production, are not expected to gain advantages shortly because of inadequate computational intensity and a shortage of integration routes (McKinsey, 2025) .
Secondly, there is considerable variation in algorithmic maturity. Although optimisation and simulation algorithms are well-suited for logistics and drug discovery, industries like healthcare services and energy distribution encounter a lack of quantum algorithms tailored to their specific domains. According to Preskill, quantum advantage remains contingent on specific problems and numerous practical issues have not yet been effectively translated to current quantum hardware (Preskill, Quantum Computing in the NISQ era and beyond, 2018).
Third, financial and structural limitations have an impact, since quantum solutions necessitate substantial investment in infrastructure, training and collaborative development with technology vendors. Smaller companies or sectors with low innovation intensity may find it difficult to justify these investments. A Boston Consulting Group survey found that over 60% of executives consider quantum to be "highly relevant" for their sector; however, fewer than 20% are currently investing, pointing to uncertainty regarding return on investment and the absence of clear strategies (BCG, 2024).
Ultimately, regulatory and ethical concerns may hinder adoption in sensitive areas. In healthcare, the application of quantum for optimising patient data brings up concerns regarding adherence to data protection regulations (GDPR). In finance, authorities caution that systemic risks may arise if quantum technology is implemented inconsistently among institutions (ECB, 2024).
Expert Michele Mosca of the University of Waterloo stated, “Quantum will not serve as a universal solution." It will deeply change certain industries, whereas others might

experience only slight advantages" (Mosca, 2022). This viewpoint emphasises the importance of targeted adoption approaches where Europe should avoid universally applying quantum and instead focus on sectors that exhibit the greatest readiness, economic impact and potential for cross-industry benefits.
Moreover, the skills gap continues to be a fundamental obstacle to implementation. In spite of Europe's attempts to grow its quantum workforce via initiatives like the Quantum Competence Framework, the quantity of engineers and developers educated in quantum algorithms, cryogenic electronics and hybrid workflows remains inadequate. The OECD (2023) highlights that the lack of qualified workers ranks as one of the three main barriers to industrial quantum adoption, especially for SMEs that do not have the means to hire or develop experts (OECD, A QUANTUM TECHNOLOGIES POLICY PRIMER, 2025) .

A further challenge relates to standardisation and interoperability. The European Quantum Industry Consortium highlights that the lack of standardised APIs, benchmarking protocols, and middleware hinders companies from implementing applications across various hardware platforms (QuIC, 2025). McKinsey (2025) also points out that the absence of standardised guidelines acts as a barrier to moving from research prototypes to solutions that can be commercially scaled. In the absence of harmonisation, companies face the danger of vendor lock-in and restricted cross-industry applicability of quantum solutions.

Ultimately, the quantum ecosystem is susceptible to hype cycles and exaggerated expectations. Studies warn that despite the excitement surrounding demonstrations of "quantum supremacy," practical applications in most industrial settings are still years off. Exaggerating short-term advancements could create disappointment for investors and policymakers, resulting in a lack of funding for essential long-term infrastructure (Osaba, et al., 2025). This highlights the necessity for practical roadmaps that differentiate between exploratory pilot projects, medium-term hybrid implementations, and long-term objectives of fault-tolerant quantum computing.

3.2.1. Healthcare and chemistry

Healthcare and chemistry have become some of the most promising initial fields for quantum computing, due to the sector's dependence on extremely complex computational problems. As stated by Flöther, applications in this area can typically be categorized into three types: nature simulation, managing intricate structured data, and searching and optimization. In drug discovery and genomics, quantum algorithms like the Variational Quantum Eigensolver (VQE) and quantum annealing are explored to speed up molecular simulations, protein folding and DNA sequence alignment, thus facilitating the development of new compounds at lower costs and faster timelines than traditional approaches (Flöther, 2023). Diagnostic applications also gain advantages from quantum machine learning (QML), which has been used to categorize intricate medical datasets, from radiological images to genomic profiles and electronic health records, often reaching performance metrics that equal or exceed classical standards (Gupta, Wood, Engstrom, Pole, & Shrapnel, 2025). Quantum methods are also investigated in precision medicine, such as drug response forecasting, adaptive radiotherapy strategies, and epidemiological modelling (Flöther, 2023).

Apart from direct clinical uses, these computational limitations also affect molecular biology, where conventional high-performance systems face challenges with exponentially complex problems. As noted by Baiardi, essential tasks like protein folding, the exploration of conformational space, and the precise simulation of DNA and RNA structures are still unmanageable for classical computing (Baiardi, Christandl, & Reiher, 2023) . Quantum algorithms such as VQE and Quantum Phase Estimation (QPE) offer more efficient techniques for modelling the electronic structures and dynamic activities of biomolecules. These advancements may directly affect precision medicine by facilitating the detection of protein–ligand interactions and aiding in the creation of new compounds. Simultaneously, QML techniques are appearing as robust instruments for examining extensive biological datasets, including genomic sequences or microscopy data, offering predictive insights that would be challenging to achieve otherwise

In spite of this extensive potential, the application of quantum computing in healthcare and molecular biology is still mostly in the experimental phase. NISQ-era hardware currently cannot manage biologically relevant systems on a large scale, and significant advancements in error correction, scalability and hybrid quantum–classical integration will be necessary before clinically validated results can be obtained. Ethical and regulatory concerns are similarly urgent, as employing quantum algorithms on

sensitive patient information brings immediate issues regarding privacy and adherence to regulations like the GDPR.
Notably, techniques created in healthcare and molecular biology demonstrate considerable cross-industry relevance, as identical quantum methods for simulation or optimization may also promote advancements in materials science, catalysis, and energy systems. This strengthens the perception of healthcare as a strategic experimental space for quantum technologies, with developments expected to spread into associated industrial areas (Flöther, 2023).
In Europe, quantum research and development has prioritized healthcare and chemistry, fuelled by strategic public funding and private efforts. The European Union along with its Member States has invested more than €11 billion in quantum technologies in the last five years, specifically highlighting healthcare and life sciences as important application domains. In addition, the Quantum Technologies Flagship, as presented in chapter 2, continues to back projects that convert quantum breakthroughs into real-world healthcare applications, ranging from drug discovery to medical imaging.

At the project level, Horizon Europe has supported initiatives like QUANTUM (2024–2026), bringing together 35 European partners to create a health data quality and utility certification that facilitates the dependable secondary use of health data for AI and quantum workflows (DigitaleEurope, 2024). The initiative demonstrates an understanding that data infrastructures are essential for impactful quantum applications in genomics, diagnostics and epidemiology. National governments are increasing their efforts: Germany has put over €2 billion into quantum technologies since 2020, encompassing research centres and HPC-quantum integration platforms (Reuters, Germany aims to be world leader in quantum technologies, says Scholz, 2024), whereas Denmark has introduced a quantum hub aimed at boosting biotech and medical research capabilities (Kleja, 2025). In France, companies like Pasqal and Qubit Pharmaceuticals are rising as leaders in quantum-enhanced chemistry and drug development, backed by national funding initiatives and European innovation programs (Wrzosinski, 2025).

Insights gathered from European stakeholders provided support for these observations. A representative from Qubit Pharmaceuticals, a Franco-American deep-tech firm focused on quantum-enhanced drug discovery, emphasised that hybrid quantum–HPC methods are vital not only to overcome existing hardware restrictions but also to act as an effective training ground for cultivating internal skills and cooperative networks. This perspective illustrates how companies with robust absorptive capacity can efficiently integrate quantum physics, AI and high-performance computing to boost innovation in intricate fields like pharmaceuticals. In addition, a spokesperson for Qubit Pharmaceuticals stressed that currently, quantum computers are not used in production settings, as the technology is still underdeveloped and needs more advancements. Instead, focus is placed on R&D, where innovative algorithms and software are crafted and initial datasets are produced. The goal is to create a "supply side" of quantum-ready data and optimisation frameworks that can be expanded when fault-tolerant quantum computers are accessible. From this viewpoint, traditional computing acts as a foundational preparation, facilitating an easier shift to quantum technology when it achieves the required standards of efficiency and dependability.

In spite of these encouraging advancements, obstacles persist. Analysts observe that private investment in quantum healthcare remains behind public funding, with venture capital being less prevalent in Europe than in the United States or Asia. Additionally, fragmentation among national programmes results in redundancies and competition for talent, which hinders efficiency. Regulatory limitations are crucial as well: the General Data Protection Regulation (GDPR) still restricts the integration of sensitive patient datasets into new quantum workflows, creating another challenge for scaling.

In summary, Europe has established healthcare and chemistry as key test environments for quantum innovation, backed by significant public funding and increasing involvement from the industry. Though the sector remains in an exploratory stage, efforts like Horizon Europe's QUANTUM project and the firms such as Qubit Pharmaceuticals suggest that the area is developing the technological and organizational skills necessary for future implementation. This focus on infrastructure and skills underscores that healthcare in Europe represents not only a valuable sector for quantum technologies but also a catalyst across industries, with techniques created in this field anticipated to influence energy, materials science, and advanced manufacturing.

Core problem	Electronic-structure simulation, protein–ligand binding, sequence alignment, imaging/classification
Quantum approaches	VQE/QPE for chemistry QAOA/annealing for combinatorial tasks QML for diagnostics
Near-term value path	Chemistry simulations to inform classical pipelines, QSAR/QML triage, experiment design
Data prerequisites	Curated molecular and omics datasets secure compute, QC–HPC connectors, validation workflows
Key risks	NISQ noise/scale, GDPR constraints, clinical validation burden
EU activity	Horizon Europe, Quantum Flagship, Pasqal, Qubit Pharmaceuticals, national HPC–QC pilots

Table 3.1.: Healthcare and chemistry

3.2.2. Energy and Smart Grids

The energy sector is viewed as one of the most promising areas for early quantum applications due to its reliance on extremely complex optimization and simulation challenges. Recent pilot initiatives demonstrate the application of quantum optimization algorithms, including the Quantum Approximate Optimization Algorithm (QAOA) and hybrid VQE methods, in grid balancing, energy trading and predictive maintenance.

QAOA, initially aimed at solving combinatorial optimization challenges, has demonstrated significant applicability in grid balancing, as it can estimate optimal power distribution among distributed energy resources during varying demand. Its capability to directly integrate constraints into the quantum circuit renders it appropriate for scheduling issues like unit commitment or load distribution in smart grids (Farhi, Goldstone, & Gutmann, 2014). In contrast, hybrid VQE techniques, which merge quantum state preparation with classical optimization cycles, are being increasingly utilized for network optimization and material simulations. In energy systems, VQE has been used to represent the dynamic behaviour of storage elements and to replicate molecular interactions in battery substances (Bauer, Bravyi, Motta, & Chan, Quantum Algorithms for Quantum Chemistry and Quantum Materials Science, 2020) (NQCC, 2025). The hybrid aspect of VQE, depending on iterative interactions between quantum and classical processors, renders it especially feasible in the current NISQ era, as it accommodates noise while still producing approximate yet valuable solutions. Collectively, these algorithms demonstrate how various quantum approaches tackle different facets of the energy issue: QAOA offers solutions for immediate optimization and scheduling, while VQE aids in long-term advancements in materials and storage technologies.

IBM and E.ON have explored quantum-inspired techniques for optimizing smart grids and integrating renewables, showcasing the opportunities and challenges of NISQ-era technologies (BETA, 2023). Additional research indicates that quantum-enhanced models can minimize energy losses in modelled wind farms and distribution systems (NEWS, 2024). While these findings are confined to pilot projects and small-scale models, they highlight the capacity of quantum techniques to enhance classical optimization in the shift towards more sustainable and resilient energy systems. Researchers highlight that the scalability of these methods is limited by existing NISQ hardware, the lack of standardized benchmarks, and the challenges in reproducing outcomes on various quantum platforms (Ajagekar & You, Quantum computing for energy systems optimization: Challenges and opportunities, 2019) whereas frameworks combining digital twins with quantum components are under investigation to boost resilience and real-time management of smart grids (Lemo, Saber, Kundur, & Skorek, 2025). Through the development of virtual models of energy systems that dynamically engage with real-time data, these hybrid systems can enhance the integration of renewable resources, boost fault identification, and aid operators in scenario analysis and risk management. These applications not only improve technical reliability but also serve as a decision-support tool for utilities, aligning with the strategic goals of the European Green Deal and Horizon Europe energy initiatives. Nonetheless, the actual implementation of these solutions is still restricted by the computational limitations of NISQ technology and the lack of standardized interfaces connecting digital twin platforms with quantum solvers, which need to be resolved before achieving industrial scalability (Ajagekar & You, Quantum computing for energy systems optimization: Challenges and opportunities, 2019) (European Commission , 2025).

In terms of materials, hybrid quantum workflows have been employed to model battery materials, with Quantinuum showcasing NMR spectra computations for lithium-containing compounds as part of the Horizon Europe initiative (NQCC, 2025). Likewise, the Full-Map consortium led by QunaSys utilizes quantum machine learning to speed up the identification of eco-friendly battery materials (Qunasys, 2025).
For managers and policymakers, these advancements highlight both prospects and challenges. Quantum computing presents an opportunity to improve energy efficiency, speed up material discovery, and strengthen sustainability initiatives. Conversely, the underdeveloped state of existing hardware and the unpredictability of ROI complicate the decision-making process significantly. Strategic decisions focus on when to invest, whether to cultivate internal quantum skills or depend on partnerships, and how to weigh short-term inefficiencies against long-term competitiveness. In this regard, early pilots focus more on developing capabilities, mitigating risks and getting organizations ready for when quantum devices attain fault tolerance rather than solely surpassing classical systems.

At the European level, these technological and management efforts correspond with policy initiatives. The Quantum Europe Strategy 2025 clearly designates energy and climate technologies as key sectors for quantum applications, seeking to link scientific advancements with industrial autonomy and climate neutrality goals (European Commission , 2025). By integrating quantum development into wider sustainability and industrial strategies, Europe establishes the energy sector as both a testing ground for quantum innovation and a catalyst for cross-industry spillovers. Techniques and understandings established here can transition to related fields like logistics, materials, and manufacturing, strengthening the view of quantum computing as a revolutionary facilitator throughout the European economy.

Core problem	Unit commitment, grid balancing, maintenance scheduling, battery/materials modelling
Quantum approaches	QAOA/annealing for dispatching and scheduling issues in energy networks, VQE to simulate materials/chemistry by estimating electronic energies and properties useful for selecting new compounds, QML for forecasting
Near-term value path	Decision support for dispatch, materials pre-screening, digital-twin augmentation
Data prerequisites	Real-time telemetry, market and asset data, orchestration with SCADA/HPC/AI
Key risks	Benchmark scarcity, integration with OT, ROI tied to hardware progress
EU activity	IBM–E.ON pilots, EuroHPC/EuroQCS nodes, battery consortia (for example: Quantinuum/QunaSys)

Table 3.2.: Energy and Smart Grids

3.2.3. Logistics and Supply Chain

The logistics and supply chain industry offers one of the most attractive areas for the early implementation of quantum computing, since numerous fundamental issues, like vehicle routing, scheduling, network design, inventory optimization and warehouse management, become computationally unmanageable when applied to real-world complexities. These issues are generally NP-hard and include dynamic limitations, positioning them as strong contenders for quantum enhanced optimization.

A thorough study by Phillipson validates this view, classifying quantum uses in logistics into six main areas: routing, network design, fleet optimization and upkeep, cargo loading, forecasting and inventory management, and scheduling. The assessment emphasizes that most existing techniques are hybrid quantum-classical methods, integrating classical solvers with quantum subroutines to address the hardware constraints of present-day NISQ devices. Of the examined paradigms, quantum has been most frequently utilized because of its capacity to handle larger problem instances, whereas gate-based methods like the Quantum Approximate Optimisation Algorithm (QAOA) and Variational Quantum Eigensolver (VQE) are also being researched, though they face more significant scalability limitations.

The existing literature has predominantly concentrated on routing and scheduling issues, as these can be easily represented using quadratic unconstrained binary optimization (QUBO) models. Conversely, applications of prediction and machine learning are still somewhat overlooked, even though they could enhance demand forecasting, inventory control, and supply chain robustness. Significantly, Phillipson emphasizes that although quantum computing probably won't precisely resolve NP-hard problems, it could offer considerable benefits in generating high-quality approximate solutions more quickly than traditional heuristics, especially in multi-objective scenarios where cost, service level and sustainability must be concurrently managed (Phillipson, Quantum Computing in Logistics and Supply Chain Management - an Overview, 2025).

Recent industry reports further emphasize specific corporate efforts investigating quantum-enhanced logistics. According to Lingaro Group, automotive companies like BMW Group and Volkswagen have tested quantum algorithms to solve intricate optimization issues in their supply chains. BMW has utilized recursive QAOA for addressing bin packing and partitioning challenges, whereas Volkswagen has employed quantum methods to enhance urban traffic navigation. These proof-of-concept initiatives demonstrate how international companies are starting to confirm the capabilities of quantum computing in practical scenarios, especially for problems that traditional approaches find difficult to address effectively. In addition to routing and scheduling, quantum techniques are anticipated to enhance supplier selection, production planning, and demand forecasting, leading to more robust and sustainable supply chains. The report also predicts that the “quantum computing as a service” sector might achieve USD 26 billion by 2030, emphasizing the financial significance of these technologies and the potential for their use in logistics in the coming decade (Kreft, 2025).

Outside the automotive industry, worldwide logistics companies are starting to incorporate quantum computing into their innovation strategies. DHL has partnered with IBM and Honeywell to explore quantum optimisation for last-mile delivery and fleet routing, emphasizing real-time factors like weather, fuel costs, and customs delays. These pilots emphasize the potential of hybrid quantum workflows to decrease delivery times, enhance fleet utilization, and reduce fuel usage (DHL, 2025). Likewise, Maersk has acknowledged quantum technologies in its Logistics Trend Map 2025, predicting that uses in routing, predictive analytics, and network planning might generate USD 50–100 billion in worth by 2050. The firm highlights that logistics enhanced by quantum technology might aid in reducing supply chain interruptions and bolstering resilience during crises like pandemics, geopolitical tensions or climate-related incidents (Firth, 2025).

The European Union has likewise emphasised logistics and supply chains in its strategic framework. The Quantum Europe Strategy (2025) emphasises transport and logistics as sectors of cross-industry significance, directly associating them with sustainability goals. Pilot initiatives within Horizon Europe and the Quantum Flagship feature investigations into routing optimisation, demand forecasting, and sustainable logistics. These efforts seek to not only create algorithms but also to build infrastructures, hybrid HPC–quantum platforms, open-source toolkits, and benchmarking protocols, that can be utilised across various sectors. By aligning quantum advancements with the European Green Deal, the EU positions logistics as a proving ground for technologies that can both improve efficiency and mitigate environmental impact.

Nonetheless, numerous significant obstacles persist. Present demonstrations are generally confined to proof-of-concept models utilising simplified datasets, whereas the intricacy of actual supply chains, marked by numerous echelons, variable demand, and shifting constraints, surpasses the capabilities of NISQ-era devices. The scalability of quantum algorithms is additionally limited by qubit noise, brief coherence times, and challenges in encoding extensive datasets into quantum states. Additionally, there is currently no agreement on standardised benchmarks for logistics applications, complicating the comparison of results among various studies and platforms. Various experiments assess success based on cost reductions, computation duration, or precision, resulting in inconsistent evidence that hinders industry implementation.

Another challenge is the gap in skills. Logistics companies seldom have internal knowledge of quantum algorithms and must depend on partnerships with tech vendors, academic institutions, or startups. Developing absorptive capacity, the capability of an organisation to identify, incorporate and utilise external knowledge, becomes essential. In the absence of this capability, companies may lag as quantum technologies develop. On the vendor side, firms providing Quantum-as-a-Service (QaaS) platforms are anticipated to significantly reduce entry barriers for logistics companies by offering cloud-based access to hardware and ready-made optimisation modules. Industry experts anticipate the QaaS market may hit USD 26 billion by 2030, highlighting the financial prospects of these services (Lingaro Group, 2024).

Anticipating the future, it is generally believed that quantum computing in logistics will take a hybrid path. Upcoming implementations are anticipated to include quantum subroutines integrated within classical optimisation frameworks, especially for addressing subproblems like local route optimisation or container packing. Comprehensive end-to-end quantum logistics systems will only be possible with the arrival of fault-tolerant devices that can manage thousands to millions of qubits. During this period, initial users will concentrate on enhancing capabilities, experimenting with quantum algorithms on smaller issues, and creating quantum-ready datasets that can be utilised once hardware efficiency increases.

From a management and policy viewpoint, the European example emphasises the necessity of synchronising quantum adoption with strategic objectives like sustainability, resilience, and industrial independence. With Europe making substantial investments in quantum infrastructure, logistics presents a logical application area that links technological advancement with wider societal goals. The methods and knowledge produced here are anticipated to extend into interconnected sectors like manufacturing, energy, and healthcare, strengthening logistics' position as a testing ground and a cross-sector driver for quantum technologies.

Core problem	Vehicle routing, bin packing, network design, inventory and scheduling
Quantum approaches	QAOA/annealing (QUBO formulations), hybrid variational solvers, emerging QML
Near-term value path	Subroutine speedups inside meta-heuristics, multi-objective trade-offs
Data prerequisites	Clean graph instances; simulators/annealers, QaaS access, API-ready data
Key risks	Real-world complexity and NISQ, skills gap, lack of common benchmarks
EU activity	BMW/VW proofs-of-concept, EU Green Deal–aligned pilots, QaaS vendors active

Table 3.3.: Logistics and Supply Chain

3.2.4. Finance and risk analysis

Finance has consistently been recognised as one of the most promising areas for the early implementation of quantum computing, mainly due to the industry's reliance on resolving computationally demanding issues within tight time and regulatory limits. Risk management, portfolio optimisation and derivative pricing often necessitate the simulation of high-dimensional systems or the solving of NP-hard optimisation problems, which classical algorithms typically approximate at significant computational expense. Quantum computing can speed up these processes, allowing for more precise and prompt decision-making in capital markets, banking and insurance.

Simulation is a key application domain. As noted by Egger, quantum amplitude estimation offers a quadratic acceleration compared to classical Monte Carlo methods, which are commonly used for option pricing, value-at-risk (VaR) assessments, and credit risk analysis. These activities are essential not only for valuing financial products but also for meeting regulatory standards, especially under Basel III/IV guidelines regarding capital adequacy and stress testing (Egger, et al., 2020). Proof-of-concept implementations on IBM Quantum devices have already shown the viability of pricing basic derivatives and assessing risk measures, though on a restricted scale.

Optimisation represents another encouraging area, especially in asset allocation and portfolio management. Traditional algorithms for mean-variance optimisation, created by Markowitz, become computationally unmanageable when augmented with practical constraints like transaction costs, cardinality limits, and non-linear risk metrics. Quantum algorithms like the Quantum Approximate Optimisation Algorithm (QAOA) and hybrid variational techniques are currently under investigation to address these intricate formulations. Initial trials by financial firms, such as JPMorgan and Goldman Sachs, have utilised quantum optimisation methods for portfolio diversification and trade settlement, indicating the industry's awareness of quantum computing's game-changing capabilities.

Machine learning in finance signifies a third area of focus. Quantum-augmented ML techniques are being explored for uses like fraud detection, anomaly identification in transaction flows, credit assessment and know-your-customer (KYC) procedures. Due to the rapid expansion of financial datasets, quantum machine learning methods could enable quicker pattern identification and predictive modelling compared to classical algorithms, although existing findings are still in early stages.

Despite these prospects, various obstacles and restrictions hinder immediate implementation. The primary issues include the hardware constraints of NISQ-era devices, such as noise, limited qubit numbers and brief coherence durations. Loading data into quantum states continues to be a significant limitation, since financial models generally encompass extensive historical datasets that are expensive to encode on quantum hardware. Additionally, concerns regarding algorithmic reliability, shortages in skilled personnel and adherence to regulations must be resolved prior to the implementation of quantum finance solutions in operational settings.

In the future, many experts expect that the initial practical quantum advantage in finance will arise in hybrid quantum–classical workflows, where quantum subroutines speed up the most resource-intensive aspects of simulation or optimization processes.

The financial sector is actively gearing up for this change: organizations like JPMorgan, HSB and BBVA have established specialized quantum research teams, while the Bank for International Settlements has highlighted the immediate need for quantum-safe cryptography to address long-term security threats. Finance and risk analysis not only showcase a primary application domain for quantum technologies but also reflect the wider preparedness of the sector to serve as an early adopter, linking research with commercial application.

In Europe, finance has emerged as one of the most strategically significant sectors for early quantum implementation, due to its ability to enhance computationally demanding tasks and the threats it presents to digital security. The Quantum Europe Strategy (2025) clearly identifies finance as a key sector, acknowledging the dual necessity of harnessing quantum possibilities, such as risk simulation, optimisation, and cryptography, while addressing risks to vital infrastructure (European Commission , 2025).

On the regulatory front, the Coordinated Implementation Roadmap for Transitioning to Post-Quantum Cryptography (PQC), released in June 2025, mandates that EU Member States initiate transition activities by 2026, which encompass cryptographic inventories and migration plans, aimed at protecting high-risk sectors like finance and telecommunications by 2030 (European Commission , 2025). This is consistent with the Bank for International Settlements (BIS), which in its 2025 report advised financial institutions globally to evaluate vulnerabilities immediately, emphasizing that “harvest-now, decrypt-later” attacks pose immediate threats even prior to the availability of fault-tolerant quantum computers (BIS, 2025). The European Central Bank has also warned that inconsistent adoption of quantum technologies among financial institutions might create systemic risks (ECB, 2024).

Tangible industrial indicators further illustrate European involvement. The Spanish company Multiverse Computing focuses on quantum and quantum-inspired algorithms for optimizing portfolios and analysing risks, collaborating with leading European banks to experiment with proof-of-concept projects (Multiverse Computing , 2023). Major players like HSBC, BBVA, and Deutsche Bank have established specialized quantum research teams or partnered with IBM and Google Quantum AI to investigate derivative valuation, settlement efficiency, and risk assessment. At the hardware level, European startups such as IQM Quantum Computers (Finland) are enhancing the continent's computational ability, having secured more than €300 million to create systems capable of facilitating hybrid HPC-quantum workflows pertinent to financial simulations (IQM, 2025).

Intesa Sanpaolo is among the first financial institutions in Italy to investigate quantum computing. The bank has carried out exploratory work on quantum-enhanced risk analysis, portfolio optimization, and Monte Carlo simulations on hybrid HPC–quantum platforms in partnership with national research infrastructures like CINI and CINECA. These efforts, while still in their early stages, demonstrate how complex financial modelling can be supported by quantum algorithms and how major incumbents in the Italian banking industry are starting to assess their quantum readiness. This case demonstrates how the use of quantum in finance is not just being adopted by international players but is also progressively spreading throughout the Italian innovation ecosystem (Intesa San Paolo, 2022).

Even with these encouraging advances, various obstacles impede acceptance. Financial institutions in Europe are experiencing fragmentation, with resources and capabilities concentrated in a limited number of Member States, particularly Germany, France, Spain, and Finland, resulting in smaller markets being less equipped. Furthermore, ROI uncertainty continues to be significant, as numerous pilots are confined to controlled environments or limited data sets. Data governance and regulatory compliance introduce additional challenges: GDPR and financial regulations demand strict verification and auditability, which hampers the speed of experimentation with quantum workflows.

Experts predict that Europe's initial significant quantum advantage in finance will arise from hybrid quantum–classical processes, especially in Monte Carlo acceleration, value-at-risk assessment, and constrained portfolio optimization. Simultaneously, the adoption of PQC is essential: both European and global organizations stress that safeguarding financial infrastructure from quantum risks must advance irrespective of the speed of algorithmic advances. Finance thus serves as a primary application area for quantum technologies and a benchmark for Europe's regulatory and infrastructure preparedness, with success reliant on harmonizing technological advances with systemic risk oversight.

Core problem	Monte-Carlo pricing, VaR/CvaR, constrained portfolio optimization, fraud/KYC
Quantum approaches	Amplitude Estimation, QAOA/variational optimizers, QML for anomalies
Near-term value path	MC subroutines for Greeks/VaR, constrained portfolio heuristics, sandboxed QML
Data prerequisites	High-quality market/credit data, audit trails, QC–HPC integration, PQC roadmap
Key risks	Data-loading cost, regulatory auditability, model risk, NISQ limits
EU activity	Banks' quantum teams (HSBC, BBVA, DB), EU PQC roadmap, Multiverse partnerships

Table 3.4.: Finance and risk analysis

3.2.5. Manufacturing and discovering new materials

Manufacturing and materials innovation stand out as a crucial domain where quantum computing is anticipated to create significant change. In contrast to various fields where quantum applications are still theoretical, the simulation of materials and chemical systems is fundamentally quantum-mechanical, aligning it closely with the capabilities of new quantum hardware. Conventional high-performance computing (HPC) has achieved significant milestones in simulating molecular interactions, catalysis, and advanced alloys; however, it encounters exponential scaling challenges when dealing with strongly correlated systems, reaction pathways, or extensive active spaces in quantum chemistry (Bauer, Bravyi, Motta, & Chan, Quantum algorithms for quantum chemistry and quantum materials science, 2020). These computational limitations hinder innovation in areas as varied as energy storage, semiconductor development, sustainable plastics, and aerospace materials. Quantum computing, functioning directly on quantum states, presents a completely novel approach for addressing these issues.

Multiple categories of quantum algorithms have been recognized as valuable resources for production and the discovery of materials. The Variational Quantum Eigensolver (VQE) and its variants are some of the most researched methods, aimed at estimating the ground-state energies of materials and molecules. Their mixed characteristics, where a quantum apparatus generates test wave functions and a classical optimizer fine-tunes parameters, render them appropriate for the noisy intermediate-scale quantum (NISQ) period. Recent studies indicate that the effectiveness of VQE is greatly influenced by the choice of ansatz, the qubit mapping, and the optimization procedures (Sivakumar, et al., 2024). The Quantum Phase Estimation (QPE) algorithm, albeit more demanding in resources, offers chemically precise simulations once fault-tolerant technologies are accessible.

Recent advancements in algorithms feature the Cascaded VQE (CVQE) created by the U.S. Naval Research Laboratory, enhancing processing efficiency by breaking down large eigenvalue issues into smaller, manageable subspaces. This method has cut down the simulation durations for ground-state computations from months on traditional HPCs to hours on hybrid systems. Alternative hybrid approaches, like perturbative VQE extensions, exhibit promise for simulating periodic materials using shallow quantum circuits, enhancing their feasibility on existing devices (Liu, Li, & Yang, 2024).

In addition to chemistry simulation, quantum optimization methods like the Quantum Approximate Optimization Algorithm (QAOA) and quantum annealing have been investigated for production scheduling, job-shop optimization, and workflow planning in manufacturing settings (Phillipson, Quantum Computing in Logistics and Supply Chain Management - an Overview, 2025). These issues are NP-hard and escalate quickly with system size, positioning them as ideal targets for quantum-boosted approximate solutions. Ultimately, Quantum Machine Learning (QML) methods are being explored for detecting anomalies in predictive maintenance, recognizing patterns in sensor networks, and optimizing digital twins for industrial systems (Shamsuddoha, Kashem, Nasir, Hossain, & Ahmed, 2025).

Engagement between industry and quantum for materials is increasing rapidly. BASF and Dow have partnered with quantum technology firms to model catalysts and polymers, intending to expedite R&D processes and lower experimental expenses. OTI Lumionics, a startup from Canada and Europe, has developed quantum-inspired algorithms to simulate excited states, reaction pathways, and electronic correlations pertinent to optoelectronic materials like OLEDs (OTI Lumionics, 2025). These activities demonstrate how industrial research is shifting from solely theoretical explorations to focused proof-of-concept implementations.

Volkswagen and ExxonMobil are testing quantum workflows in the energy and automotive industries to investigate advanced batteries and fuel cells. These efforts correspond with Europe's strategic drive for energy transition, as advanced materials are essential for electric vehicles and hydrogen technologies. Likewise, the Quantum-Integrated Discovery Orchestrator (QIDO) platform introduced in 2025 by Mitsui, QSimulate, and Quantinuum offers a unified environment for discovering drugs and materials. QIDO merges quantum processors with HPC workflows, specifically crafted to reduce design cycles and enhance precision in material simulations (Quantinuum , 2025).

Startups are likewise engaged, for example Algorithmiq in Finland creates hybrid quantum algorithms for discovering drugs and materials, whereas French-based Pasqal works with pharmaceutical and industrial partners on quantum-improved simulations of intricate systems. The Full-Map consortium, led by QunaSys alongside European collaborators, utilizes quantum machine learning to speed up the discovery of sustainable battery materials (Qunasys, 2025).

European research efforts validate this direction. The UK's National Quantum Computing Centre (NQCC) has created resource benchmarks for simulating lithium-based compounds pertinent to batteries, illustrating the performance of current devices against prospective logical-qubit architectures (NQCC, 2025). Horizon Europe initiatives have additionally fostered international partnerships focused on battery chemistry and eco-friendly catalysts, while Fraunhofer institutes in Germany collaborate with IBM to investigate hybrid HPC-quantum workflows in industrial chemistry.

Europe has made significant financial and strategic commitments to quantum technologies in manufacturing and materials. Over the past five years, the EU and its Member States have invested more than €11 billion in quantum R&D, of which a significant share has gone into hardware, chip development, and application-driven projects relevant for materials and production.
The EU Chips Joint Undertaking has allocated €145 million by 2025 to support pilot lines for quantum chips, directly relevant to manufacturing and hardware ecosystems (JU, 2024). In addition, the European Investment Fund (EIF) has invested €30 million in the French venture capital fund Quantonation II, which specialises in early-stage quantum technologies including materials-focused startups (EIF, 2025). National governments complement these EU-level investments: Germany has committed over €2 billion since 2020, including the establishment of IBM's quantum data centre and Fraunhofer-led consortia on materials simulation (Reuters, 2024). Finland's IQM Quantum Computers raised about €320 million in 2025, reaching a valuation above €1 billion, with support from the Finnish state fund Tesi, to expand hardware manufacturing capacity (IQM, 2025). France, through its national quantum plan, has supported startups such as Pasqal and Qubit Pharmaceuticals, both active in chemistry and material science.
These investments illustrate a shift from pure scientific research to industrial-scale infrastructure, including fabrication facilities, pilot lines and cloud-based quantum access. They position Europe not just as a consumer of quantum technologies but as a potential leader in the quantum manufacturing value chain.

Even with significant progress, the area encounters ongoing constraints. Present NISQ devices have limited qubit numbers, are susceptible to noise, and lack comprehensive error correction, limiting both the scale and precision of simulations. Transforming extensive material datasets into quantum states continues to be resource intensive. Standardization poses another challenge: the European Quantum Industry Consortium points out the lack of unified APIs, benchmarking standards, and industrial metrics, which hinders interoperability and raises the risk of vendor lock-in.

Economic difficulties are also urgent. Despite robust public funding, private investment remains wary, particularly for deep-tech startups in materials discovery, due to lengthy and uncertain ROI timelines. The skills gap adds to the problem: the

OECD (2023) highlights deficiencies in engineers proficient in quantum algorithms, cryogenic electronics, and hybrid HPC–quantum workflows as among the three primary obstacles to industrial adoption.

The discovery of materials enhanced by quantum technology has broad implications across industries. Developments in battery chemistry directly impact the energy sector, allowing for more effective integration of renewables. Advancements in catalysts can revolutionize both chemical production and renewable fuels. Methods of simulation created for drug discovery can be applied to polymers and advanced composites. Consequently, tools for manufacturing optimization created for scheduling in factories can be utilized in logistics networks.

From a strategic perspective, Europe acknowledges that quantum computing won't substitute classical HPC but will act as a supplementary enhancer. Hybrid quantum–classical workflows are anticipated to prevail in the near future, as quantum processors handle subproblems that classical systems struggle to address efficiently. This is in accordance with the European Commission's focus on quantum-centric supercomputing, incorporating quantum devices directly into HPC systems (Choucair, 2024).

To sum up, manufacturing and materials exploration are some of the initial fields expected to show concrete advantages from quantum computing. The alignment of scholarly research, industrial experiments, and significant European funding indicates robust progress. Nevertheless, the industry's future will hinge on addressing technological challenges, creating interoperability standards, and developing a skilled workforce adept at connecting physics, computation, and practical application. By tackling these challenges, Europe can establish itself as a worldwide frontrunner in quantum-enhanced manufacturing, utilizing quantum technologies to enhance industrial competitiveness while also promoting sustainability and strategic independence.

Core problem	Ground/excited states, catalysis, job-shop and flow-shop scheduling, predictive maintenance
Quantum approaches	VQE/CVQE, QPE (FT future), QAOA/annealing (scheduling), QML for PdM
Near-term value path	Materials down-selection, scheduling subproblems, twin calibration
Data prerequisites	Materials databases, lab-automation links, hybrid QC–HPC toolchains
Key risks	Noise/scale, standardization gaps (APIs/benchmarks), deep-tech funding cycles
EU activity	Fraunhofer–IBM, IQM hardware, EU Chips JU pilots, Pasqal/industry collaborations

Table 3.5.: Manufacturing and discovering new materials

3.3. Connecting industrial domains with quantum hardware technologies

Although the algorithmic and managerial ramifications of quantum computing across industries have been discussed in the preceding sections, it is equally pertinent to look at how sectoral applications and quantum hardware architectures align.

Variations in qubit technologies' coherence time, scalability, gate fidelity, connectivity, and operating conditions have a direct impact on how well-suited they are for different industrial issues.

Due to their scalability and compatibility with current cryogenic infrastructure, superconducting qubits, which are currently used by IBM, Google, and IQM, dominate the market. They are appropriate for hybrid optimisation and simulation tasks, including those in materials, logistics, and finance, due to their quick gate operations.

With longer coherence times and higher gate fidelities, trapped-ion systems. which are employed by IonQ, Quantinuum, and Alpine Quantum Technologies, show promise for applications in quantum chemistry and medicine where accuracy and stability are more important than speed.

Photonics-based methods are outstanding in linear-optical networks and room-temperature operation, indicating promise in quantum communication, AI-driven analytics, and data-intensive industrial pipelines.

Promoted by Pasqal and QuEra, neutral atoms are being investigated more and more for large-scale simulation and optimization, bridging the gap between the trapped-ion and superconducting paradigms.

Lastly, annealing architectures, like D-Wave, are already used commercially and are especially useful for combinatorial optimization, which is pertinent to manufacturing scheduling, logistics, and energy dispatch.

The following is a summary of this relationship:

Industrial sector	**Key computational problems**	**Most compatible hardware technologies**	**Motivation**
Healthcare and chemistry	Molecular simulation, drug discovery (VQE, QPE)	Trapped ions, superconducting, neutral atoms	High precision and coherence are needed, early pilots use trapped ions (Quantinuum, IonQ).
Energy and smart grids	Optimisation, materials design (QAOA, VQE)	Superconducting, annealing, neutral atoms	Hybrid HPC integration and quick gate times for materials R&D and scheduling
Logistics and supply chain	Routing, scheduling (QAOA, annealing)	Annealing, superconducting, neutral atoms	Proofs-of-concept have already used annealers, scalable lattice models show promise

Finance and risk analysis	Simulation, portfolio optimisation (Amplitude Estimation, QAOA)	Superconducting, photonics	Photonics shows promise for sampling tasks, while high-speed circuits are well-suited for stochastic simulations
Manufacturing and materials	Catalysis, job-shop optimisation (VQE, QAOA)	Superconducting, trapped ions, neutral atoms	Stable, mid-scale systems are well suited for simulation-intensive workloads; neutral atoms scale effectively.

Each architecture currently holds a strategic niche, with no single hardware platform dominating all domains.

Interoperability between these technologies will become essential to future competitiveness as Europe develops its hybrid HPC–quantum infrastructure through national initiatives and EuroQCS.

Policymakers and businesses can thus prioritize investments where hardware maturity best supports industrial relevance by mapping the alignment between technological readiness (TRL) and sectoral potential.

3.4. Economic and competitiveness implications across sectors

The sectoral examples outlined in this chapter illustrate that quantum computing is evolving not merely as a specialized instrument confined to a single field, but as a general-purpose technology (GPT) whose influence is both cumulative and systemic. Healthcare, energy, logistics, finance and manufacturing represent initial sectors where quantum computing could generate value, but their importance goes far beyond singular uses. As emphasized earlier in section 3.1, the ability to achieve cross-industry transferability is heavily reliant on absorptive capacity and innovation capability. These ideas form the basis for comprehending how sector-specific pilots can expand into competitive practices across the economy and influence macroeconomic results.

A key implication is the possible enhancement of European competitiveness and productivity through quantum technologies. Quantum techniques specifically address computational limitations in valuable sectors: molecular simulations reduce R&D timelines in pharmaceuticals, quantum-boosted routing enhances logistics effectiveness, risk assessment speeds up compliance in finance and material simulations facilitate the creation of innovative catalysts and batteries.
When examined separately, these results might appear minor, instead, when combined, they signify systemic productivity improvements that can circulate throughout the European economy.
According to the Boston Consulting Group (2023) and McKinsey (2025), it is projected that quantum adoption might contribute between USD 450 billion and USD 1 trillion each year to global GDP by 2040. If Europe succeeds in securing even one-fifth of this value, it would signify a significant boost to growth, particularly in areas vital to the EU's industrial policy (BCG, 2024) (McKinsey, 2025).
Equally important are the spillover and transfer impacts across different areas. As mentioned in section 3.1, quantum algorithms like the Variational Quantum Eigensolver (VQE) and the Quantum Approximate Optimization Algorithm (QAOA) possess intrinsic versatility. Improvements achieved in one field, such as drug discovery, can frequently be utilized in other areas, like advanced polymers or sustainable fuels, as long as the intended sectors possess the ability to assimilate them. This dynamic illustrates the concept of analogy-driven and technology-based transfer, wherein innovations cross the boundaries of various industries. From a European viewpoint, this ability for cross-sectoral transfer is not just a theoretical concept but a practical necessity to optimize returns on public investment. Horizon Europe initiatives in health data and energy materials, for instance, demonstrate how infrastructure created for a specific use case can foster innovation in related fields.

From a macroeconomic perspective, the significance of these cross-sectoral interactions is evident through metrics like productivity, employment, trade balance and investment streams. Productivity increases directly result from quicker design processes, streamlined operations and improved modelling capabilities. Job creation is focused on high-skilled positions, quantum engineers, cryogenic specialists, algorithm developers, which produce multiplier effects in regional ecosystems, evident in hubs like Munich, Paris-Saclay, Espoo and Barcelona. In terms of trade, creating local hardware and software diminishes dependence on foreign suppliers, retaining value added within Europe. The €145 million investment by the EU Chips Joint Undertaking in quantum chip pilot lines (2025) illustrates how large-scale industrial infrastructure can stabilize supply chains within Europe. At the same time, Europe's expanding quantum ecosystem draws foreign direct investment, as international technology companies more frequently collaborate with European research institutions and startups.

However, converting advancements in quantum technology into lasting GDP growth is not guaranteed. As mentioned earlier in the sector analyses, fragmentation, skill gaps and lack of standardisation continue to be significant challenges. In the absence of coordination, Member State initiatives may duplicate efforts instead of providing complementary support, which could undermine economies of scale. Likewise, as emphasized by the OECD (2023), the lack of professionals trained in quantum technology is a fundamental obstacle to adoption. These constraints directly influence Europe's capacity to translate scientific leadership into macroeconomic results.

A further challenge is the danger of excessive hype, especially noticeable in financial markets. In early 2025, stock values of firms such as IonQ, Rigetti, and D-Wave surged significantly, reaching as high as 2,000% in certain instances, after news of acquisitions, government deals and hardware achievements (Frąckiewicz, 2025). This increase shows that markets are progressively viewing quantum potential as genuine, but it also indicates volatility and speculative excitement. As highlighted by Mosca stated that quantum will not equally revolutionize all sectors, and overly optimistic expectations might result in disillusionment if advancements slow down. For Europe, the message is obvious: macroeconomic advantages rely on consistent, coordinated investment and skill development, rather than fleeting financial cycles (Mosca, 2022).

Collectively, the findings indicate that the relationship between quantum development in Europe and economic results is influenced by absorptive capacity, innovation capability and transferability, which are the same foundational concepts detailed in section 3.1. Companies and ecosystems possessing robust absorptive capacity, like Qubit Pharmaceuticals in life sciences or Pasqal in advanced simulation, are currently illustrating how sectoral innovation can be scaled and disseminated. In macroeconomic language, this indicates that quantum implementation boosts not just competitiveness in specific sectors but also overall resilience, industrial independence and sustained GDP expansion.

Quantum computing must be recognized as a cross-sector catalyst with impacts that exceed the total of its industry-specific uses. Europe's capacity to achieve economic benefits hinges not just on technological innovations but also on organizational preparedness, policy coherence and ecosystem collaboration. Through harnessing absorptive capacity and facilitating innovation transfer, Europe can transform quantum technologies from disjointed pilot projects into a unified catalyst for competitiveness and economic advancement. This positioning is essential for the continent to transition from a scientific leader to a macroeconomic beneficiary of the quantum revolution.

Examining the sectoral analyses outlined in this chapter reveals a distinct conclusion: quantum computing is not only a technological aspiration but also a reflection of Europe’s inherent strengths and vulnerabilities. The continent showcases remarkable scientific achievements, dynamic startups, and robust public investment approaches. Conversely, fragmentation, shortages in skills, and restricted private investment continue to pose considerable obstacles that may hinder the conversion of research into industrial and macroeconomic results.

What stands out to me is how the ideas of absorptive capacity, innovation capability, and cross-industry transferability, introduced at the start of this chapter, emerge as critical elements in every field. Finance gains from robust regulatory demands and tangible pilots, healthcare progresses through hybrid HPC–quantum frameworks, logistics acts as a testing ground for multi-objective optimization, and materials science showcases Europe’s enduring dominance in chemistry and physics. However, the rate at which these sectors advance past pilot stages relies more on their capacity to incorporate external expertise, synchronize stakeholders, and tactically manage immediate risks alongside long-term prospects.

I think the primary challenge for Europe is not just achieving quantum advantage in individual applications but also ensuring coherence and transferability between different sectors. A disjointed ecosystem, in which each Member State or sector seeks quantum adoption independently, exposes efficiency and global competitiveness. On the other hand, if Europe succeeds in turning pilots into scalable infrastructures, aligning national initiatives, and cultivating a talented workforce, quantum computing could evolve into more than a scientific milestone; it may serve as a driver for sustainable competitiveness, industrial autonomy, and enduring GDP expansion.

This chapter ultimately emphasizes that quantum technologies ought to be viewed not as objectives in themselves but as a foundational layer of innovation, like to the historical significance of electricity or the internet. Their worth will arise not from individual advancements but from their incorporation into intricate socio-technical frameworks, where preparation, management and foresight will be as crucial as qubits or algorithms.

Chapter 4 A strategic framework for industrial adoption

4.1. Positioning existing adoption models in the quantum computing context

The integration of new technologies has typically been examined through various conceptual frameworks that aim to clarify how innovations spread, develop and ultimately become part of industry practices. Some of the most impactful include Rogers' Diffusion of Innovations, the Technology Readiness Level (TRL) framework and its variations, the Technology Acceptance Model (TAM) and the Dynamic Capabilities viewpoint. Every one of these frameworks provides a useful perspective for grasping adoption dynamics, yet when used in the context of quantum computing, they expose important shortcomings. Quantum technologies, in contrast to earlier digital advancements, are marked by significant uncertainty, intricate ecosystem interdependencies, expensive infrastructures and extended development timelines, resulting in a less straightforward and predictable adoption process compared to other tech areas.

The TRL, TAM and Dynamic Capabilities frameworks, which each highlight distinct aspects of how emerging technologies move from experimentation to broad adoption, are examined in more detail after Rogers' Diffusion of Innovations.

Rogers' theory is commonly used to illustrate the diffusion of innovations among groups, transitioning from early adopters to late majority, influenced by factors like relative advantage, compatibility, complexity, trialability, and observability. In quantum computing, though, these parameters only partly reflect adoption dynamics. Trialability and observability continue to be constrained as access to quantum devices is confined to cloud environments, and the outcomes frequently remain unclear to non-experts. In the same way, the comparative benefits of quantum solutions are not yet clearly evident for most industrial scenarios, leading adoption choices to focus less on visible advantages and more on strategic placement. Consequently, diffusion trends in quantum are significantly influenced by ecosystem preparedness, vendor tactics, and government regulations, elements not specifically addressed in Rogers’ framework.

The Technology Readiness Level (TRL) framework is still a key tool for assessing technological maturity, as was covered in Chapter 1. TRLs are reviewed in the context of this strategic framework, though not to explain the technical advancement, but to emphasise the managerial implications for investment choices and adoption timing.

Technology Readiness Levels are widely recognised as a standard method for evaluating technological maturity. Their advantage comes from offering a straightforward path from idea to implementation, a terminology that resonates with policymakers and funding organisations. In the realm of quantum, TRLs highlight a dual challenge: the development of hardware platforms and the preparedness of applications and business cases progress along distinct paths. Additionally, the infamous valley of death separating TRL 4 and TRL 7 is especially pronounced in quantum technologies because of expensive infrastructure, scarce private funding and ambiguous commercial routes. Extensions like Q-TRL or e-TRL seek to tackle certain problems by incorporating criteria specific to the domain or sufficiency after deployment, yet they continue to be mainly centred on technology. They provide minimal direction on organisational, strategic, or market preparedness, which are essential for companies assessing the timing for initiating pilots or expanding investments.

The Technology Acceptance Model has demonstrated its value in situations where adoption choices depend on personal views of utility and user-friendliness, particularly in digital and software areas. In contrast, quantum computing is a deep-tech area defined by B2B utilisation, extended development periods, and indirect advantages. In this context, adoption hinges not on individual user approval but on the dedication of the organisation and its strategic vision. Evaluating metrics like perceived usefulness becomes challenging when the commercial worth is unclear and timelines are not fixed. Consequently, TAM offers minimal input for shaping adoption strategies within the quantum field.

Finally, the dynamic capabilities framework, focused on sensing, seizing and transforming in reaction to technological shifts, aligns more closely with the quantum scenario. Companies need to continuously review roadmaps, capitalise on chances for experimentation and modify their frameworks to support hybrid infrastructures and emerging skills. Nonetheless, this model remains very conceptual. Although it outlines the strategic necessities, it fails to detail how to assess readiness or establish concrete milestones for quantum implementation.

Collectively, current adoption frameworks emphasise important elements of the adoption process but do not offer a cohesive pathway for quantum technologies.

Rogers discusses diffusion yet misses ecosystem interdependencies, TRLs reflect technical advancement but disregard organisational and strategic preparedness, TAM emphasises end-users yet omits systemic industrial choices and dynamic capabilities highlight strategic direction but fall short on operational indicators. This results in companies and policymakers lacking the necessary resources to connect technical progress with strategic implementation. The lack of such a framework is especially significant in the quantum realm, where early investments might lead to sunk costs and delayed adoption could involve strategic setbacks. Hence, there is a necessity to combine technical and application preparedness with organisational elements, ecosystem circumstances, and strategic goals, offering both businesses and policymakers practical advice for managing the ambiguities of quantum integration.

As a result, businesses and policymakers lack clear tools to match technological maturity with strategic decision-making, leading to a fragmented understanding of quantum adoption. A comprehensive framework that integrates technical and organisational readiness, ecosystem conditions and strategic alignment is urgently needed, as delayed engagement runs the risk of strategic obsolescence and premature investment can result in sunk costs. The Quantum Adoption Pathway (QAP) model is used in the next section to suggest such a strategy.

4.2. Design of the strategic adoption framework

Considering the lack of a thorough model that focuses on the industrial adoption of quantum computing, this thesis presents a Quantum adoption pathway (QAP), a conceptual framework that integrates knowledge from traditional adoption theories with data from recent industry analyses and interviews.

This framework aims to translate the principles of current adoption models into a workable, step-by-step roadmap for quantum technologies, where uncertainty, ecosystem interdependence and long timelines render conventional diffusion patterns insufficient.

In particular, the QAP is intended to help organisations navigate the various phases of quantum engagement, from proof-of-concept and exploration to integration, scaling and leadership, all the while coordinating technological maturity with ecosystem conditions, strategic intent and organisational readiness.

By determining the best entry points, resource allocations and risk management techniques for quantum adoption, this framework seeks to assist managers and policymakers.

As a result, in settings marked by rapid technological evolution and uncertainty, it functions as both a diagnostic tool and a strategic framework for decision-making. Decision-makers in large and medium-sized businesses are supposed to use this roadmap as a managerial guide.

The QAP facilitates a methodical and knowledgeable approach to implementing quantum technologies by outlining this process, making sure that every stage is in line with both corporate preparedness and technological viability.

The framework presented in this chapter is a unique contribution of the author and is meant to serve as a workable route for industrial adoption. The model is purposefully non-temporal and does not specify implementation timelines, though, because of the quick and unpredictable evolution of quantum hardware and software.

4.2.1. The framework's methodological foundation

Theoretically, the order of the five stages reflects the logic of dynamic capabilities: companies identify new technological signals during the exploration phase, then use experimentation in the proof-of-concept stage to seize opportunities, and finally, through integration, scaling, and ecosystem leadership, they gradually alter their structures and processes. The dynamic capabilities framework's description of the cumulative, path-dependent nature of capability building is reflected in the progression from cognitive awareness to ecosystem-level leadership.

The interviewees represented diverse viewpoints from big tech companies, start-ups, telecommunications, hardware developers, and application-focused businesses. They came from a range of organizations within the quantum ecosystem, including Google, QuantumNet, Orange System, Seeqc, Planckian, Quera, Qubit Pharmaceuticals, and QuIC.

From an empirical perspective, interviewees' narratives demonstrated a common understanding that quantum adoption is a slow, capability-driven process that is still in its early stages, even though they did not specifically outline any frameworks. According to the majority of respondents, organizations are still in the exploratory or pilot stages, concentrating on developing capabilities rather than deploying them operationally. This supported the notion that, in order to bridge theoretical concepts with actual practice, a multi-phase, non-temporal model would best represent the current state of industrial quantum adoption. Consequently, the Quantum Adoption Pathway (QAP) is not only a theoretical synthesis but also a direct reaction to the empirical data collected: businesses need a road map that leads them from the first technological signals to the stage of organizational and ecosystem leadership.

As a result, the five phases of the QAP are not a descriptive taxonomy but rather an analytical synthesis, with each phase representing a unique set of organizational capabilities and decision gates that are consistent with the evolutionary dynamics postulated by the literature on absorptive capacity and dynamic capability.

4.2.2. Quantum adoption pathway

A structured model called the Quantum Adoption Pathway (QAP) was created to depict the various phases that organisations go through as they consider, test, and ultimately incorporate quantum technologies. As outlined in the previous section, this study advances the QAP proposed by the author as a deliberately atemporal model.

It describes a spectrum that progresses from awareness to strategic leadership, reflecting the increasing technological sophistication of quantum systems as well as the changing preparedness of the organisations implementing them.

Each of the five primary phases identified: exploration, proof of concept, integration, scaling and leadership and ecosystem shaping, is linked to specific objectives, difficulties and organisational capacities.

In reality, these phases frequently overlap or iterate, despite the sequence's apparent linearity. This reflects the experimental and co-evolutionary nature of quantum adoption.

4.2.2.1. Exploration phase

Organisations first start interacting with the new field of quantum technologies during the exploration phase. At this point, since the interest is more cognitive and strategic than operational, managers want to know what quantum computing is, how it's different from traditional methods and whether it could be useful for their sector. Building a common understanding of the technology's potential, uncertainty and timelines is the goal rather than developing solutions just yet.

This initial stage is in line with what innovation management scholars refer to as sensemaking, which is the process by which businesses decipher unclear technological signs and turn them into strategic narratives (Cristofaro, 2022). This task is especially difficult in the context of quantum computing since most corporate managers are not familiar with the underlying science and the anticipated uses are still unknown. In order to understand the state of the art and spot possible opportunities, organisations frequently turn to outside sources of expertise, such as research consortia, public programs and consulting networks.

Horizon scanning, technology intelligence and involvement in quantum innovation ecosystems, such as through workshops hosted by national quantum initiatives, partnerships with start-ups, or academic collaborations, are typical managerial moves during the exploration stage. At this point, a lot of businesses commission quantum readiness assessments to analyse their current infrastructure gaps and competencies. These evaluations usually look at three areas: first, human capital and data science, artificial intelligence, and simulation skills, second, digital maturity and access to high-performance computing resources and third, strategic openness to disruptive innovation.

Establishing an internal quantum task force or innovation observatory that reports to the R&D or strategy department is frequently necessary for the exploration phase from an organisational standpoint. Coordinating knowledge acquisition, keeping an eye on vendors and serving as an internal liaison for new opportunities are the responsibilities of this team. Through their cloud platforms, early-stage partnerships are established with major players like IBM Quantum, Quantinuum, or Pasqal, enabling limited experimentation without making significant financial commitments. Through Qiskit Runtime, which offers usage-based pricing tiers and exposes real hardware on the IBM Cloud, businesses can conduct small pilots without having to commit to long-term contracts or upfront capital expenditures. Through the Nexus platform and software stacks, Quantinuum provides cloud access to its H-Series systems. Jobs are completed using Hardware Quantum Credits (HQCs), enabling controlled budgeting and proof-of-concept runs (Quantinuum, 2025) . Additionally, Pasqal offers a managed cloud service for its neutral-atom processors, enabling partners to test integrations and workloads prior to making any on-premise commitments (Pasqal, 2025).

However, there are a number of difficulties with the exploration stage as well. First, some businesses misallocate resources due to inflated expectations about the short-term benefits of quantum computing brought on by the hype surrounding it.
Second, internal understanding is usually fragmented: senior executives frequently find it difficult to relate algorithmic concepts to business value, even though technical staff may understand them.
Third, it is challenging to defend exploratory spending to shareholders due to the absence of standardised benchmarks for evaluating possible impact. Because of this, a lot of businesses continue to adopt a "wait-and-see" mentality, watching advancements without preparing internally to take action when the technology reaches a mature state.
Companies need to hit a number of important benchmarks in order to move past exploration. In fact, they must identify at least one high-potential application area where quantum techniques may perform better than classical ones, form early alliances with suppliers or academic institutions and set aside a modest but steady R&D budget for testing.
The organisation moves into the Proof-of-Concept stage at this point, when quantum computing is incorporated into its larger innovation radar.
To put it briefly, the exploration phase establishes the strategic and cognitive framework for every stage. It turns quantum computing from a theoretical technological curiosity into a real field with strategic importance, one that necessitates focus, organised study and careful financial planning. In addition, Figure 4.1. present a non-temporal phase diagrams that synthesise purpose, inputs, core activities, outputs and gate criteria for the Quantum adoption pathway.

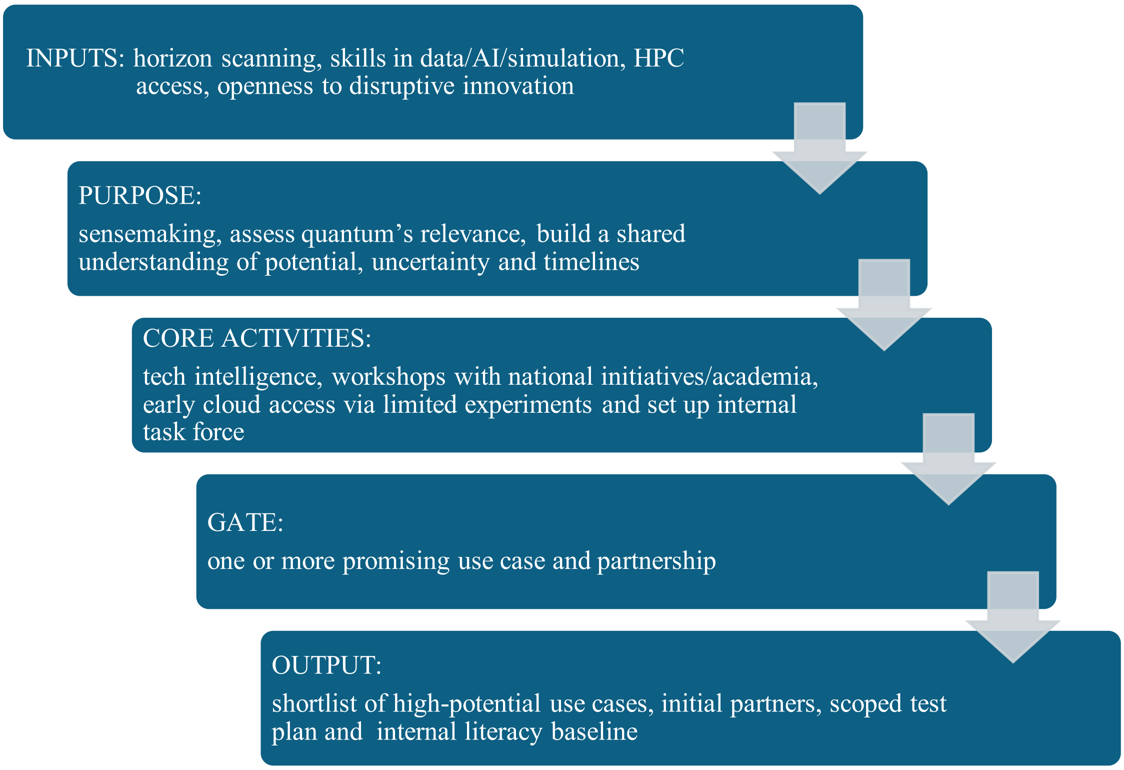

Figure 4.1.: Exploration. Phase overview summarising purpose, inputs, core activities, gate and outputs.

4.2.2.2. Proof-Of-Concept

The first concrete stage in converting strategic awareness into useful experimentation is the Proof of Concept (PoC) phase.

Small-scale, controlled experiments are used by organisations to confirm the technical viability and possible commercial value of quantum computing following the exploratory phase of sensemaking and opportunity scanning.

This phase's primary goal is to test whether quantum algorithms can be applied to actual or representative problems while also building internal capabilities and collaborations that will facilitate future integration.

Rather than being a performance-driven investment, the PoC phase serves as a learning laboratory from a strategic perspective. By observing how quantum technologies behave in real-world scenarios, what kinds of issues they can solve and potential organisational or technical obstacles, managers can lessen uncertainty.

Choosing a quantum use case, which is an operational or analytical problem that is computationally intensive and has properties that could benefit from quantum advantage, like combinatorial optimisation, molecular simulation or complex risk analysis, is frequently the first step in this stage.

Examples include material design simulations, logistics routing and portfolio optimisation in finance, all of which have been investigated by early adopters like BMW, Airbus, BASF[13] and JPMorgan in partnership with suppliers of quantum technology.

At this point, managerial activities centre on cooperation, testing and developing capabilities. Through joint research agreements, businesses typically form alliances with software developers, hardware vendors, or academic institutions.

Cloud-based platforms like IBM Quantum, Amazon Braket, or Microsoft Azure Quantum, which offer simulators and early-stage processors for testing, are usually the best way to access quantum resources.

From the perspective of implementation, data scientists and engineers can create quantum circuits and variational algorithms that are suited to particular use cases by developing pilot projects using frameworks such as Qiskit[14], Cirq[15], PennyLane[16] or Ocean SDK[17].

The majority of projects use hybrid approaches, which combine quantum elements with traditional optimisation techniques. For example, the Quantum Approximate Optimisation Algorithm (QAOA) is used for combinatorial tasks and the Variational Quantum Eigensolver (VQE) is used for molecular energy estimation.

From an organisational standpoint, new interdisciplinary teams that bridge the technical and business domains are brought about by the PoC phase. Data scientists, operations researchers, IT architects and innovation managers are frequently included in quantum working groups that businesses create.

---

[13] A multinational chemical company based in Ludwigshafen, Germany. Among the biggest producers of chemicals worldwide, with operations in the areas of materials, industrial solutions, surface technologies, nutrition, care, and agricultural solutions. Alongside academic and startup partners, BASF investigates quantum-computing use cases, such as materials simulation and optimization.

[14] Qiskit is the world's most popular and performant software stack for quantum computing and algorithms research. Build, optimize, and execute quantum workloads at scale.

[15] An open-source framework for programming quantum computers.

[16] PennyLane is a Python 3 software framework for differentiable programming of quantum computers.

[17] Ocean Software is a suite of open-source Python tools accessible via the Ocean software development kit (SDK) in GitHub.

These groups are delegated to convert business issues into mathematical expressions that can be used with quantum hardware, such as QUBO[18] or Hamiltonian representations[19].

Simultaneously, the company starts to find internal people who serve as intermediaries between the business and quantum domains, promoting cultural acceptance and facilitating communication.

In contrast, there are also significant obstacles during the PoC stage: first, it can be challenging to define realistic success metrics because proof of concept projects typically yield qualitative results rather than immediate economic benefits, intended as proof of feasibility and not profitability. Second, the size and complexity of solvable problems are limited by hardware constraints in the era of Noisy Intermediate-Scale Quantum (NISQ). The physical constraints of current qubit counts, error rates, and coherence times must therefore be taken into consideration when designing pilot projects. Third, unrealistic timelines or excessively high management expectations can lead to organisational misalignment. Executives frequently underestimate the amount of time needed for experimentation in order to produce consistent outcomes.

Additionally, the number of parallel PoCs a company can maintain may be constrained by the cost of experimentation, both in terms of human resources and cloud access.

Leading organisations use structured evaluation frameworks for their PoC initiatives in order to reduce these risks.

Three sets of metrics are commonly included in these frameworks: algorithm performance, noise sensitivity and resource efficiency are examples of technical feasibility metrics.

Successfully navigating the proof-of-concept phase typically results in the development of initial governance frameworks for quantum innovation as well as a quantifiable improvement in internal quantum literacy.

Additionally, the company began creating a quantum knowledge base by recording partner evaluations, algorithm performance and lessons learned. Later stages,

[18] The standard form known as QUBO (Quadratic Unconstrained Binary Optimization) maps a problem to an Ising model and encodes it as minimizing a quadratic function over binary variables (0/1). It is frequently used as a target form for mapping to gate-based hybrid solvers and to express combinatorial problems for quantum annealers.

[19] Hamiltonian representations: a problem is expressed as an energy operator, or Hamiltonian, whose ground state contains the solution. Widely used in optimization by mapping costs and constraints to Ising-type Hamiltonians, so that minimizing energy equates to solving the original task, and in quantum simulation.

especially integration and scaling, where decisions are based on the body of evidence gathered from PoC activities, require these insights as crucial inputs. When experiments yield repeatable outcomes and a clear picture of how quantum computing can benefit the organisation is formed, the move from proof of concept to integration takes place. This is usually indicated by the creation of a specific unit for quantum innovation or by the incorporation of quantum projects into the larger corporate R&D portfolio.

At this point, quantum adoption progresses from exploratory pilots to a formal program with budgets, goals and governance procedures.

In conclusion, the Proof-of-Concept stage converts the theoretical possibilities of quantum computing into useful organisational insights. It enables businesses to confirm viability, pinpoint obstacles and develop the internal and external networks required for extensive deployment. For a schematic overview of the QAP phases, see Figures 4.2., which summarise for each phase the purpose, inputs, activities, outputs and gate criteria.

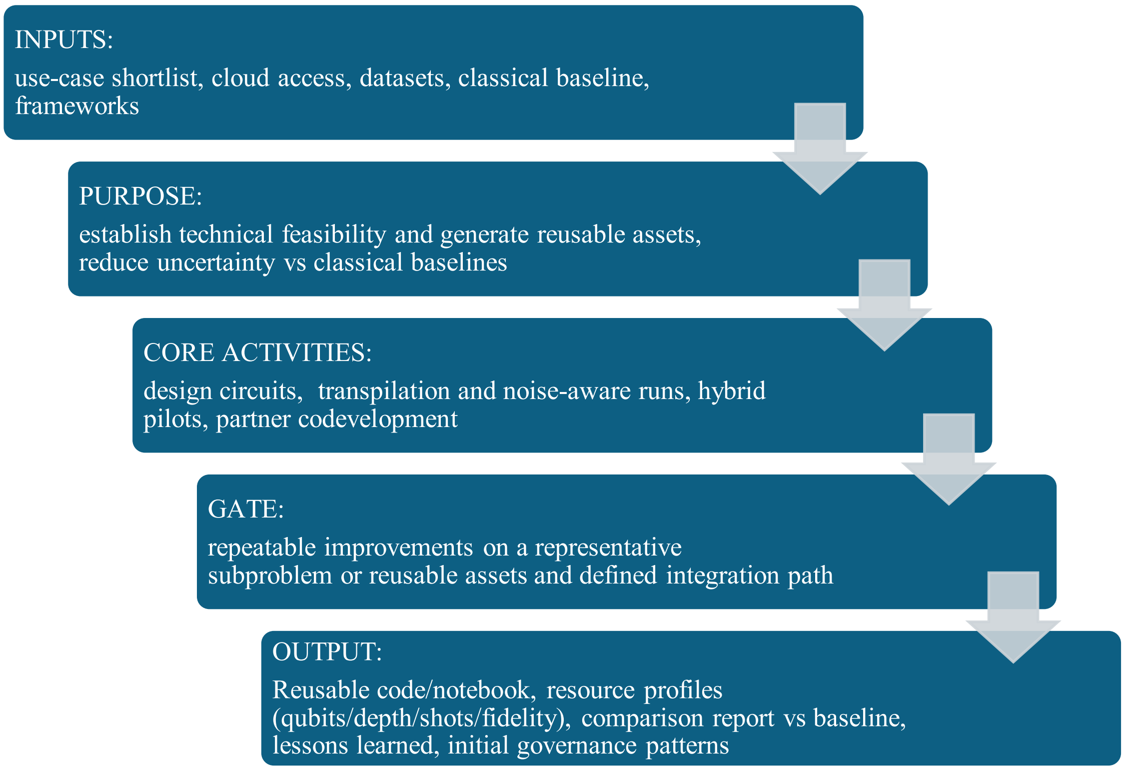

Figure 4.2.: Proof of Concept. Phase overview summarising purpose, inputs, core activities, gate and outputs.

4.2.2.3. Integration phase

The crucial shift from isolated experimentation to the organisation's operationalisation of quantum technologies occurs during the integration phase. At this point, businesses start to integrate quantum solutions into their current systems, workflows and business plans, going beyond the Proof of Concept. The main goal is to create a hybrid quantum-classical infrastructure that can accommodate both conventional computational resources and quantum applications. This stage necessitates strategic alignment of quantum initiatives with business objectives and the integration of new quantum algorithms with current IT architectures, talent structures and business processes.
Quantum computing can usually be transformed from a side project to a fundamental feature integrated into an organisation's operational architecture once it reaches the Integration phase. These days, quantum solutions are essential components of bigger systems that spur innovation and improve corporate performance rather than merely being research or pilot projects.
At this point, businesses create specialised quantum teams that include members from R&D, IT, operations, and business development, among other departments. These interdisciplinary groups are in charge of making sure that quantum-based tools are incorporated into the company's current IT infrastructure and that quantum algorithms complement business goals.

This phase of quantum technology integration is frequently hybrid, with quantum systems interacting and coexisting with classical computing resources, particularly in fields where quantum advantage has been proven (e.g., material simulations, optimisation, machine learning). For instance, hybrid quantum-classical algorithms such as the Quantum Approximate Optimisation Algorithm (QAOA) and Variational Quantum Eigensolver (VQE) are increasingly being used, in which quantum processors solve subproblems while classical systems handle pre and post-processing. Establishing cloud access to quantum systems, which enables staff members from different departments to access quantum resources remotely, is one of the main tasks in the integration phase. From simulators to early-stage quantum devices, well-known platforms like IBM Quantum, Amazon Braket, and Microsoft Azure Quantum provide a variety of quantum processors that easily integrate into current computational infrastructures. Companies can scale their quantum experiments without investing in costly, on-premise quantum hardware thanks to the ability to rent quantum computing time on the cloud.

Organisations concentrate on producing not only technical know-how but also project managers, data scientists and business analysts who are fluent in quantum technology and can effectively communicate with business stakeholders, since it is important to build internal capability.

Quantum technologies need to be completely in line with the company's long-term objectives in order to transition from experimental pilots to strategic assets. Companies usually review their investment portfolios during the integration phase to make sure quantum initiatives are appropriately incorporated into overarching business plans.

Knowing how quantum computing fits into the larger framework of digital transformation and sustainability objectives is essential to this alignment. For instance, businesses with significant investments in big data analytics, high-performance computing, or artificial intelligence frequently see quantum as an auxiliary technology that can advance these fields in the future. In a similar vein, businesses that prioritise sustainability might look for quantum solutions to replicate intricate chemical reactions or materials that can aid in the creation of green technologies or energy-efficient solutions.

Organisations also concentrate on coordinating their quantum initiatives with funding programs from the public and private sectors during this phase. In order to obtain outside funding for expanding their quantum operations, many businesses take part in extensive national or European quantum initiatives like Horizon Europe, Quantum Flagship, or public-private partnerships. These collaborations frequently offer chances for co-innovation with other participants in the quantum ecosystem, including startups, technology suppliers, and research institutes.

With explicit KPIs pertaining to advancement in quantum use cases, integration schedules, and the development of new business models, the internal quantum program is usually integrated into the organisation's strategic R&D roadmap.

It takes significant capability building to incorporate quantum computing into an organisation's operations. To make sure that their employees have the skills needed to work with quantum systems, businesses concentrate on internal training initiatives as well as talent acquisition during this phase.

To design, implement, and manage quantum-based projects, one needs specialised project managers, data scientists, and quantum engineers. However, interdisciplinary teams that can integrate domain and computational expertise are frequently required due to the complexity of quantum computing, particularly in its hybrid form. For instance, teams would need to collaborate with both machine learning specialists and quantum engineers in the case of quantum machine learning or quantum-enhanced AI. The phase's change management component is just as crucial because incorporating quantum technology frequently necessitates a change in organisational culture from one that is technology-centric to one that is innovation-centric, where quantum computing is seen as a component of the larger digital ecosystem rather than a stand-alone tool. To manage the cross-functional nature of quantum initiatives, this change may also require the creation of new governance frameworks, collaboration structures and decision-making procedures.

Additionally, companies must make sure that their quantum programs are sustainable. To do this, they must establish clear plans for scaling quantum initiatives and incorporate them into long-term growth strategies that take into account both business value and technological advancement.

There are numerous strategic and operational obstacles during the integration phase. First, as businesses strive to balance classical and quantum resources, the intricacy of hybrid quantum-classical systems may lead to technical bottlenecks. Underutilization of quantum resources is frequently the consequence of the performance difference between early-stage quantum devices and classical systems. Organisations must therefore carefully plan quantum-classical workflows to maximise each technology's advantages while preventing performance deterioration. Second, there is a significant problem with organisational alignment: although some departments may be excited about quantum technology, others may be sceptical, particularly if the potential benefits are still unknown. It will take executive leadership, good communication, and change management techniques to overcome this scepticism and promote acceptance throughout the company. Lastly, it is important not to undervalue the cost of incorporating quantum computing into corporate operations. Establishing a long-term business case that supports the investment is crucial for organisations because quantum infrastructure, talent, and continuous development can be costly. This includes being aware of the uncertain return on investment (ROI) schedules for quantum-based innovations.

The successful validation of quantum applications and the creation of scalable infrastructure signal the shift from the Integration phase to the Scaling phase. This usually happens when it is demonstrated that quantum solutions provide quantifiable business value, such as improved performance, lower costs, or a quicker time to market.

Organisations must increase internal quantum talent pools and scale quantum applications across departments or regions in order to make this shift. Additionally, businesses are starting to invest in private quantum infrastructures or specialised quantum hardware that can be tailored to their unique business requirements, going beyond cloud-based quantum access.

Quantum computing starts to move from the experimental stage to a crucial component of corporate operations during the integration phase. During this stage, organisations strive to develop internal capabilities, match quantum initiatives with business strategies, and integrate quantum technologies into current systems. It creates a more stable and sustainable path to the long-term adoption of quantum solutions by laying the groundwork for future scaling and integration into a larger technological ecosystem. For a concise, schematic view of the QAP, refer to Figures 4.3., which distil each phase's purpose, inputs, activities, outputs and gate criteria.

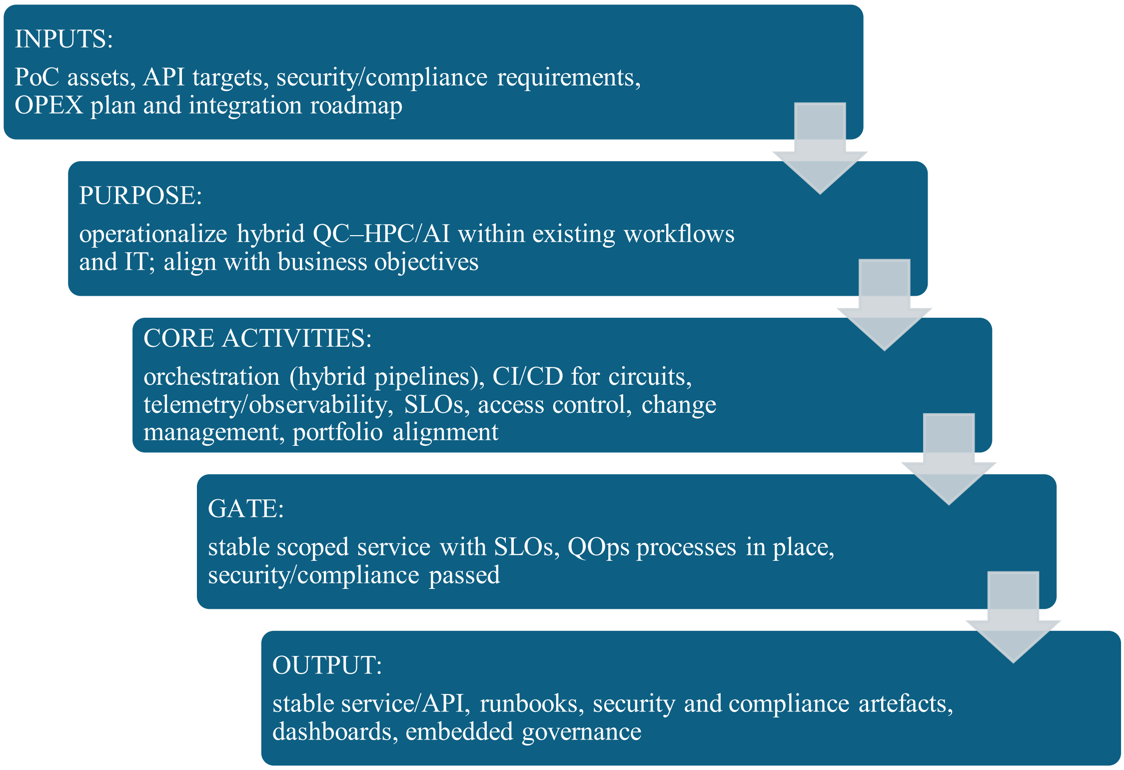

Figure 4.3.: Integration. Phase overview summarising purpose, inputs, core activities, gate and outputs.

4.2.2.4. Scaling phase

During the scaling phase, quantum computing moves from a proof of concept or pilot project to a fully functional system that can be implemented across multiple departments or even the entire company. At this point, businesses need to start growing their quantum projects and incorporating them into more comprehensive plans for digital transformation. In order to solve bigger, more complicated issues that are strategically important to the company, quantum technologies that were previously tested in isolated settings or specialised fields must now be scaled.

Moving quantum computing from pilot environments and limited use cases to enterprise-wide adoption is the aim of the scaling phase. Businesses will seek to extend the use of quantum applications to other divisions, business units, or even different regions. Quantum-enhanced algorithms for financial portfolio optimisation, for instance, could be used for enterprise-wide risk management rather than just one division. In a similar vein, quantum simulations that were first used to test product designs may be extended to supply chain optimisation or advanced manufacturing techniques.

Strategic alignment with fundamental business objectives is a crucial step at this point. Particularly in fields where quantum can enhance traditional technologies, organisations must make sure that quantum computing blends in seamlessly with their larger business transformation plans. To facilitate quicker, more precise decision-making, this may involve integration with AI, machine learning, data analytics and high-performance computing systems.
Businesses such as BMW, for instance, have already incorporated quantum-enhanced solutions into their supply chain management and logistics, connecting quantum optimisations to current production data and demand projections (BMW, 2025). Similarly, by simulating molecular interactions at scale, quantum computing aids pharmaceutical companies in speeding up drug discovery.

In order to construct the technological infrastructure required to manage greater quantum workloads, the scaling phase also calls for the investment of significant resources.
Switching from cloud-based quantum computing resources to specialised quantum hardware that can handle increasingly intricate and resource-intensive computations is one of the most important aspects of this phase. At this point, businesses can work with vendors to set up quantum data centres or invest in their own on-site quantum computing systems. Scalability, security, cost-effectiveness and quantum infrastructure maintenance are some of the aspects that should be taken into account in these investments.

Though companies looking for a competitive edge might decide to create proprietary quantum platforms or systems that better suit their data privacy, security requirements and commercial applications, IonQ and IBM, for example, provide cloud-based access to increasingly scalable quantum systems. Furthermore, collaborations with cloud service providers such as Amazon Braket or Microsoft Azure Quantum could be expanded to accomplish cross-platform integration, which would allow businesses to take advantage of the advantages of several quantum systems for various applications.

At this moment, it will be crucial to guarantee data compatibility between conventional IT infrastructures and quantum systems. Creating strong middleware and quantum-classical orchestration layers is necessary to make it possible for quantum algorithms to communicate with legacy IT systems. In order to combine the advantages of both technologies, these integrations may entail implementing Quantum-Classical Hybrid Systems, such as quantum machine learning or quantum-enhanced optimisation.

To facilitate quantum adoption on a broader scale, organisations must concentrate on staff growth and skill development during the scaling phase. Building a workforce with quantum skills that can handle increasingly complex problems and integrate quantum solutions across departments is crucial as quantum computing becomes more and more integrated into an organisation's operations.
In this sense, businesses need to make ongoing investments in hiring and training data scientists, business analysts and quantum engineers who can bridge the gap between business operations and quantum technology. This is especially important as quantum technologies advance and businesses try to fully utilise them.

Establishing a quantum centre of excellence within the company can act as a hub for best practices, innovation and knowledge exchange. In order to make sure that quantum projects are strategically in line with business goals, adequately resourced and carried out in accordance with legal requirements, a centre can also oversee and manage its governance.
Furthermore, rather than being a specialised or support tool, organisational culture needs to change to accept quantum as a fundamental part of digital transformation. This calls for leadership to support the technology and show how valuable it is to the organisation's long-term strategic goals.

Financial investment becomes a crucial component as the quantum program grows. Businesses will have to spend substantial capital and operating expenditures to support continued hardware development, talent acquisition and quantum research. The long-term goals for quantum and the unpredictability of technological advancement must be weighed against this investment, though.
Understanding the financial ramifications of quantum projects and making sure there is a clear plan for growing without overcommitting to speculative investments are key components of the risk management component of the scaling phase. This entails establishing return on investment (ROI) standards for quantum technologies and making sure that the investments are in line with the organization's overarching

business goals. Businesses can evaluate the possible risks and rewards of scaling their quantum initiatives using scenario planning and financial modelling.

Moving from a pilot-driven strategy to complete integration of quantum computing as a common enterprise capability is the ultimate goal of the scaling phase. Establishing quantum-first business strategies, incorporating quantum solutions into essential IT systems, and guaranteeing that quantum capabilities are accessible across various departments and regions are all part of this shift.
Along with supporting sustainability initiatives, improving AI capabilities and contributing to future disruptive technologies, it also entails making sure quantum computing becomes a part of the innovation ecosystem. The scalable quantum solutions created in this stage are now prepared for large-scale implementation, offering substantial commercial benefits in a number of industries.

An important turning point in an organisation's adoption of quantum technologies is the scaling phase. It necessitates significant investments in talent, technology, and resources in addition to organisational alignment with corporate objectives.
In this stage, quantum computing transforms from a research and development effort into a cohesive, value-producing part of the company that can support strategic goals and stimulate innovation. Businesses that make it through the scaling phase will be well-positioned for sustained success in the field of quantum computing and will take the lead in influencing the changing quantum ecosystem. Readers seeking a structured snapshot of the QAP should consult Figures 4.4., where each phase is summarised by its aims, inputs, key tasks, deliverables and decision gates.

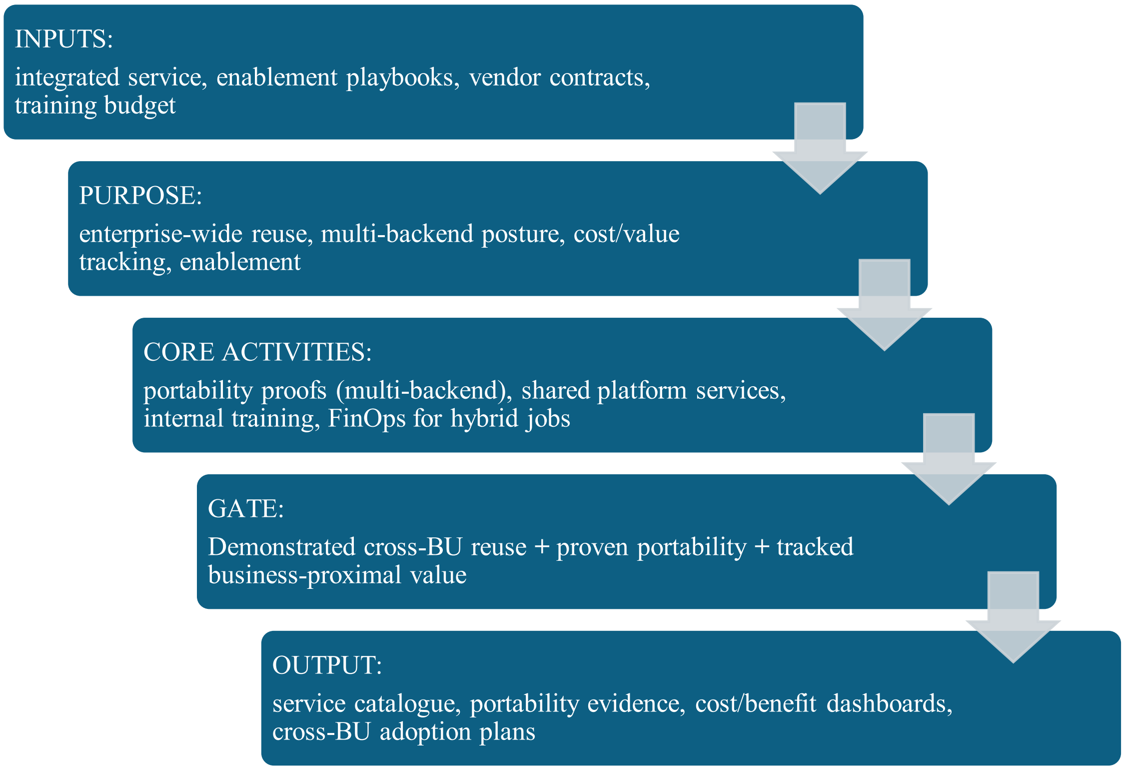

Figure 4.4.: Scaling. Phase overview summarising purpose, inputs, core activities, gate and outputs.

4.2.2.5. Leadership and ecosystem shaping phase

A company's quantum adoption journey culminates in the Leadership and Ecosystem Shaping phase, where quantum computing transforms from an experimental capability to a crucial component of industrial leadership and strategic differentiation. At this stage of development, companies actively participate in influencing industry standards, policy debates and ecosystem cooperation in addition to incorporating quantum computing into their daily operations.

Businesses that make it to this stage exhibit a high level of internal capability, a robust partner network and a clear strategic vision that links quantum technologies to long-term business objectives. In order to make sure that the company helps the quantum economy develop more broadly, the emphasis moves from adoption to leadership in innovation and long-term influence.

A strong foundation established during the integration and scaling phases is necessary to advance to the leadership phase. The organisation needs to attain operational effectiveness, technological maturity, and cultural congruence with the principles of quantum innovation.

The company's core infrastructure and decision-making procedures now incorporate quantum technologies, which are no longer merely experimental or auxiliary. Within R&D or digital transformation departments, quantum computing units frequently develop into strategic innovation divisions tasked with sustaining competitive advantage via ongoing innovation.

Currently, quantum applications are integrated into mission-critical systems and run at scale, ranging from simulation and optimisation to machine learning and cryptography.
Quantum algorithms, for instance, may be incorporated into automated trading or risk management systems in the financial industry, they may also direct real-time molecular simulations and drug development in the pharmaceutical industry, and in logistics, quantum-enhanced optimisation may boost the effectiveness of global supply chains, as discussed in Chapter 3.
Businesses create specialised quantum roadmaps to support this maturity, projecting technological advancements and coordinating them with investment planning and business cycles.
Long-term performance indicators like innovation rate, ecosystem participation, and intellectual property (IP) generation replace short-term KPIs as metrics.
Additionally, quantum governance frameworks become the norm, with explicit guidelines for cybersecurity, intellectual property sharing, and ethical use guaranteeing safe and responsible adoption.

A company's role in the quantum ecosystem becomes significant once it reaches operational maturity.
Businesses actively engage in alliances, consortia and public-private partnerships that influence the industry's course rather than working alone.
Participation in national innovation clusters, the European Quantum Industry Consortium and Quantum Flagship programs, which unite large corporations, startups, and academia to promote co-development and standardisation, as presented in Chapter 2, are a few examples.
Leading companies participate in these engagements to help define benchmarking frameworks, interoperability protocols and technical standards.

This involvement strengthens the company's strategic position within the innovation ecosystem while also advancing the collective quantum agenda.
For example, organizations can secure early-mover advantages by influencing the adoption of technologies across sectors by helping to create open-source libraries, industrial benchmarks, or quantum software toolkits.

Additionally, companies may serve as thought leaders or policy advisors in national and international debates about cybersecurity, data sovereignty and quantum ethics.
This is especially important in Europe, where projects like the European Quantum Communication Infrastructure and Horizon Europe's quantum programs are supported by the strategic goal of technological sovereignty.
Organizations can create a favourable environment for sustained leadership by influencing policy to ensure that future regulatory frameworks support both innovation and competitiveness.

During this stage, leadership is demonstrated through collaborative innovation, which goes beyond internal expertise.
Prominent companies are increasingly serving as platform orchestrators, arranging collaborations between startups, academic institutions and technology companies to jointly develop quantum applications.
By enabling shared experimentation, lower costs, and knowledge transfer across industries, this ecosystem co-creation model speeds up development.
Partnerships between Google Quantum AI and Roche, Pasqal and BASF, or IBM and Daimler, for example, show how businesses can play to each other's advantages to investigate domain-specific quantum use cases.
In a similar vein, hybrid innovation platforms that integrate high-performance computing ecosystems, AI and IoT with quantum computing allow for collective problem-solving at a scale that is impossible for lone actors.

While maintaining proprietary competitive advantages in particular applications or datasets, top companies frequently open-source portions of their codebases or research outputs to speed up global adoption.
Long-term leadership is strengthened by traits like reputation, talent attraction and collaborative credibility, all of which are improved by such strategic openness.

Developing a workforce with quantum skills throughout the entire value chain, not just within the company, is another requirement for leadership in quantum technologies.
Through training programs, academic collaborations, and specialised learning initiatives, mature companies significantly contribute to the development of the talent ecosystem.
They might sponsor doctoral fellowships, establish internal training academies devoted to quantum programming, algorithm design, and hybrid systems engineering or work with universities to create quantum engineering curricula.
This proactive approach to talent development integrates the business into the global talent network and helps guarantee a steady flow of professionals.
Leading companies support the spread of quantum expertise and the development of local innovation ecosystems by creating frameworks for knowledge-sharing and providing mentorship to start-ups or SMEs.

The organisation's quantum capabilities now provide a source of long-term competitive advantage. Value realisation, maximising the impact of quantum technologies across goods, services, and strategic operations, becomes the primary focus instead of adoption.
Quantum optimisation could increase logistics efficiency and lower carbon footprints, supporting sustainability goals, while quantum-enhanced simulations might shorten R&D cycles.
These applications improve corporate reputation and ESG (Environmental, Social, and Governance) performance, which are becoming more important in contemporary business strategies, in addition to reinforcing profitability.
The full maturity of quantum adoption is represented by the leadership and ecosystem shaping phase, where technology is thoroughly incorporated into business strategy and the advancement of society.
At this stage, organisations go beyond internal adoption to use cooperation, standardisation, and policy advocacy to impact the global quantum landscape.
They establish themselves as not just quantum-ready companies but also as quantum leaders, catalysts for a sustainable, connected, and competitive quantum future, by influencing markets, stimulating innovation, and promoting group growth. A compact representation of the QAP is provided in Figures 4.5., outlining for every phase the objective, required inputs, core activities, expected outputs and gate criteria.

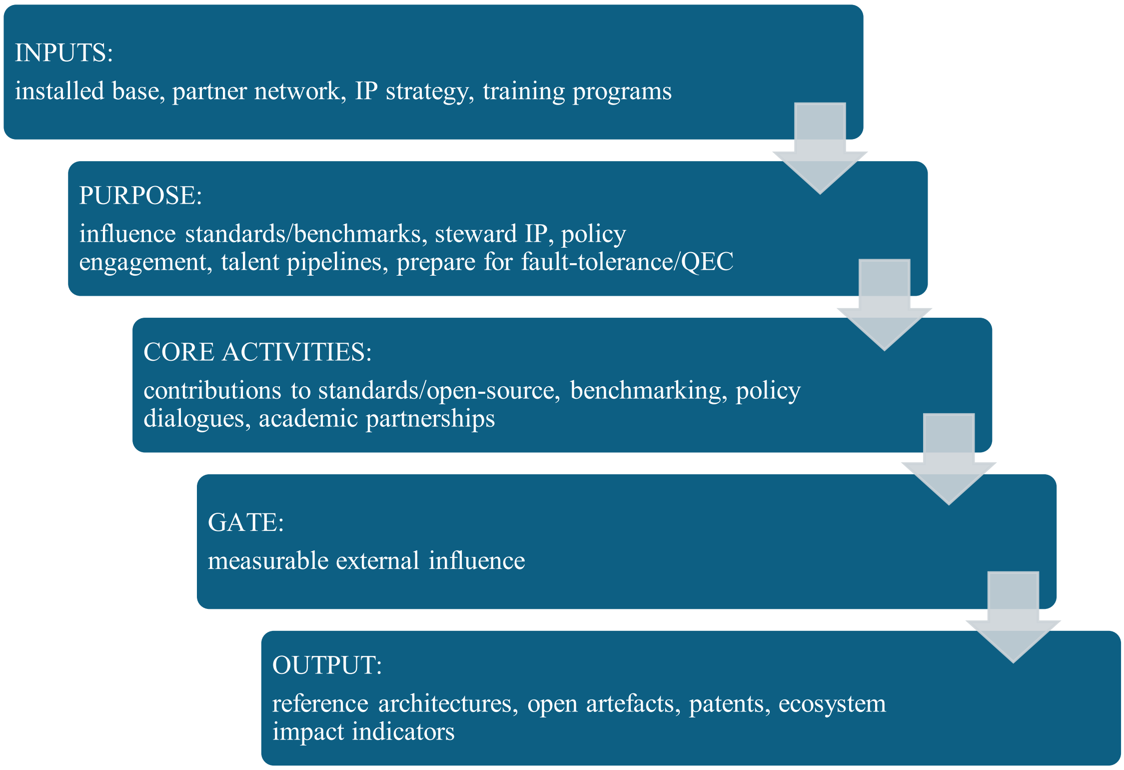

Figure 4.5.: Leadership and ecosystem. Phase overview summarising purpose, inputs, core activities, gate and outputs.

4.2.3. Competency architecture for quantum computing adoption

The Quantum adoption pathway (QAP) is not just a technology path, it is a cumulative competency architecture that shapes advancement between stages. Capability development is both phased and path-dependent in the context of quantum computing, in fact, organisations can only progress when technical expertise, organisational practices and ecosystem-facing skills are cohesive enough to facilitate dependable learning and value realisation. The competency requirements for each phase and the related evaluation standards applied at decision gates are detailed in this subsection.

This section formalises the competency requirements that support each transition, adhering to the phase structure described in Section 4.2.1. It converts the phase model into a useful capability framework for the adoption of quantum computing by connecting skills to gate assessments.

Following all the phases just described in the previous section, cognitive alignment is the competency priority during the exploration phase. Teams must be able to identify quantum-relevant structural properties, for example simulation bottlenecks, combinatorial complexity, establish reliable classical baselines and exhibit fundamental quantum computing literacy, such as state, gate and noise models. An initial partnership model and a carefully selected use-case set with first-pass resource estimates demonstrate outcome competence. When these artifacts are shared with technical and managerial audiences and can be audited, gate advancement is warranted.

Entering the second phase, teams must be proficient in variational and hybrid techniques, noise-aware experimental design and the expression of two KPIs: business-proximal, for example, time-to-solution, cost-to-quality trade-off and schedule-risk reduction and technical, such as, fidelity, approximation ratio, energy error and depth.
In this phase, the technical reformulation of a business problem into a representation that is amenable to quantum mechanics is referred to as translation. Domain experts and quantum engineers collaborate to create reusable artifacts, such as circuits, encoding templates, datasets and benchmarking scripts, that are useful beyond a single proof of concept. Only when a credible path to integration is outlined, such as explicit data contracts and stable APIs[20], and when performance is repeatable on representative instances and clearly comparable to a classical baseline, is it justified to move past the decision gate.

During the integration phase are required operational and architectural skills. Service endpoints for quantum computing workloads need to be designed by organizations, integrated into HPC/AI pipelines and subject to observability. A centre of excellence and business units own outcome competence, which is a reliable, scoped production service with documented SLOs and runbooks. Gate progression requires more than just technical viability, it also requires proof of dependability and maintainability.

Platform engineering, multi-vendor orchestration and financial operability for QC become the focus of competency at scale. Benefits are guaranteed to transfer across

[20] API (Application Programming Interface): the formally defined interface that enterprise/HPC/AI systems use to access quantum services is referred to in this context as an API. In order to facilitate dependable integration, backend portability, and auditable governance of QC workloads, it specifies endpoints and payload schemas (such as circuit formats, parameters, and result structures), authentication/authorization, versioning, and error codes.

units and geographical areas thanks to enablement capabilities, for example, internal academies, playbooks, and communities of practice.

Competencies in standards participation, benchmarking, IP strategy and policy/ethics are developed by mature adopters. The QEC[21] transition plan, which outlines when and how to switch from mitigation-heavy approaches to error-corrected regimes in accordance with external hardware roadmaps, is a forward-looking capability. Reputable reference architectures, quantifiable external contributions and ongoing talent pipelines are indicators of outcome competence. Evidence of external influence and internal renewal capacity are necessary for gate validation.

Role composition evolves with phase progression: from executive sponsor, strategy/tech scout and domain analyst to quantum algorithm engineer, data, machine learning engineer and product owner, to solution architect, security/compliance lead and finally to standards/IP lead and ecosystem orchestrator. This staged evolution avoids early over-engineering and late under-governance.

Competency assessments at each gate should follow a concise, evidence-based protocol to ensure comparability and auditability: soundness of baseline methodology and resource estimates, design treatment of noise and hardware constraints, operational ownership and hybrid integration clarity, implementation of governance, security, cost controls, portability and ecosystem engagement where applicable. Prior to re-evaluation, failure to meet criteria results in targeted remediation.

4.2.4. Limitations and further research

In light of the suggested framework takes technology maturity into account, the thresholds embedded in the decision gates, such as performance signals versus classical baselines, reliability targets and cost envelopes, may change over time because quantum computing is still in a phase where hardware roadmaps, software stacks and error-mitigation techniques are evolving quickly. Although the QAP is phase-based rather than time-based and purposefully vendor-agnostic, its operationalization necessitates regular recalibration against the state of the art.

[21] Quantum error correction

Second, generalizability is limited by cross-industry variability. The speed and viability of adoption are influenced by sectoral structures including asset intensity, regulatory pressure and data availability, problem archetypes, in particular combinatorial or simulation optimization, and ecosystem depth, notably, local partners, testbeds, public programs. For example, in the life sciences and logistics, the same gate criteria may indicate different evidence requirements.
Third, the framework assumes organizational readiness, which may not be the case in practice. The risk of a "pilot trap", intended learning without scale or, on the other hand, premature platformization, the process of formalizing pilots into an enterprise platform before reproducible, transferable value is proven, arises in the absence of minimum capability baselines.

In order to evaluate the stability and predictive validity of the gate criteria and to estimate time-to-value under alternative adoption strategies, future research should first pursue longitudinal validation of the QAP in quantum computing, tracking firms across phases. It would be feasible to determine leading and lagging indicators of transition with a panel-based design, connecting, for instance, variations in energy errors, circuit depth, effective qubit counts, or approximation ratios to downstream business-proximal outcomes like schedule-risk reduction or time-to-insight. The creation of a measurement science for QC adoption is closely related. Domain-specific challenge problems and noise-aware benchmarks, along with standardized telemetry and explicit resource estimates, would allow for reliable quantum–classical comparisons and help FinOps make decisions for hybrid QC–HPC/AI pipelines.

The framework's sectoral adaptations embody a second option. Future research should develop industry playbooks that outline data requirements, compliance constraints and integration patterns in order to calibrate the evidentiary burden associated with gate passage, given the diversity of problem archetypes, molecular property estimation in chemistry versus vehicle routing or portfolio optimization in combinatorics and finance. The study of organizational designs and governance, federated force models versus central centres of excellence, incentive programs for cross-BU reuse, procurement mechanisms with interoperability clauses, and outcome-based contracts that reward portability across vendors and backends are all naturally related to this research.

A third stream ought to conduct an empirical analysis of the competency architecture and human capital formation. Quantitative studies can test which training modalities are most effective at closing gate-critical skill gaps, as well as which role configurations, such as combinations of quantum algorithm engineers, solution architects (QC–HPC/AI), and QOps engineers, most reliably predict successful transitions between phases.

Lastly, the framework encourages expansion with layers for ethics, compliance and assurance. When combined, these research avenues would make the QAP more sector-sensitive, predictive and operationally actionable while maintaining its vendor-neutral and evidence-based nature.

Priorities for policymakers include talent tools aimed at hybrid profiles at the QC domain operations interface, challenge-led procurement to create demand signals, and interoperability and benchmarking infrastructures.

It is advised that businesses implement portfolio-based governance with clear scale rules connected to QAP gates, institutionalize QOps[22], adopt a multi-vendor posture to prevent lock-in, and consistently connect technical KPIs to business-proximal metrics including risk reduction, quality and time-to-insight. Reference architectures for hybrid QC–HPC/AI and sector templates for data governance and validation should be jointly developed by industry and policy, supported by transnational testbeds that reduce the cost of reliable evidence, especially for SMEs.

[22] Quantum Operations: the fundamental procedures for managing and operating quantum jobs in practical applications: organize circuits and versions, choose the appropriate backend, track runs (shots, time, and errors), manage queues and expenses, and deal with security and rollbacks.

Conclusions

This thesis has examined the industrial adoption of quantum computing, through a multifaceted lens that integrates organizational, policy and technological viewpoints.

The study has examined how businesses and institutions can get ready for the integration of quantum computing into larger digital transformation strategies, based on the idea that it is a potentially revolutionary general-purpose technology. The study tackled a key question: how can quantum computing advance from scientific testing to commercial application in a way that is sustainable and strategic?

The thesis' primary theoretical and practical contribution was the Quantum Adoption Pathway (QAP), an organized and empirically supported framework for addressing this issue. The framework fills a significant gap in the literature by combining empirical results from industry analyses and expert interviews with insights from established adoption theories. The uncertainty, interdependence and ecosystem complexity that characterize quantum computing are not captured by traditional models, which explain how technologies spread or develop. By tying organizational capabilities, strategic alignment and technological maturity together, the QAP bridges this gap and provides businesses with a clear road map for navigating the initial phases of quantum adoption.

By highlighting its advantages and disadvantages, the study also advances knowledge of the European quantum scene. Initiatives like the Quantum Flagship and EuroQCS show that Europe has exclusive research capabilities, a cooperative governance model, and robust public funding mechanisms. The study did identify some enduring issues, though, such as a lack of coordination between national programs, a disjointed industrial base, and a lack of venture capital investment in comparison to China and the US. According to interviewees, European stakeholders view the current stage of quantum development as pre-standardization, characterized by conflicting hardware platforms and unclear development plans. Stronger industrial policies are needed to encourage interoperability, shared benchmarking infrastructures, and cross-border cooperation in light of this fragmentation.

The cross-industry potential and readiness requirements for quantum computing are the subject of another important discovery. According to the sectoral analyses carried out in Chapter 3, the most promising early applications are found in fields like financial risk modeling, materials design, drug discovery, and logistics routing that call for intricate simulation and optimization. However, the interviews verified that true quantum advantage is still elusive and situational. Today's value is found more in the innovation processes surrounding experimentation than in direct computational gains, according to experts and representatives from QuantumNet and Planckian Technologies. In this way, the hybrid quantum–classical paradigm is a learning mechanism that facilitates capability building and ecosystem coordination rather than an operational advantage just yet.

From a managerial perspective, the QAP gives businesses a strategic and diagnostic tool to gradually engage with quantum technologies. Exploration, proof of concept, integration, scaling, and leadership and ecosystem shaping are its five distinct but adaptable phases. Each is linked to particular goals, skill sets, and gate requirements. Because firms only move forward when readiness and capability thresholds are reached, this phased structure promotes evidence-based progression. This method guarantees that technological potential and business value are aligned and lowers the risks associated with making investments too soon. The framework provides policymakers with guidance on how to focus resources on areas that will have the biggest impact, especially in creating interoperability standards, accessible testbeds for experimentation, and talent that is ready for the quantum era.

The study admits a number of limitations in spite of its contributions. First, even with the addition of numerous interviews and document analysis, the empirical evidence is still preliminary, in order to confirm the causal links between competencies and adoption outcomes, longitudinal data tracking firms across QAP phases is required. Second, hardware performance, error mitigation and software interfaces are all constantly changing in the quickly developing field of quantum computing. Therefore, in order to stay current, the framework's competency requirements and gate criteria need to be periodically updated. Third, the adoption trajectory will vary by domain due to industrial and sectoral heterogeneity; for example, finance, energy, and healthcare show different infrastructure, data, and regulatory constraints.

These restrictions suggest interesting directions for further study. First, performance metrics and readiness scales could be improved by identifying leading and lagging indicators of successful adoption through a longitudinal validation of the QAP across several industries. Second, by converting generic criteria into domain-specific guidelines, sector-specific playbooks would make the framework more actionable. Third, further research could delve deeper into the human capital dimension by mapping the training models and role configurations that best bridge capability gaps in data science, algorithm design, and quantum engineering. Last but not least, policy-focused research ought to investigate how benchmarking infrastructures, cross-border testbeds, and challenge-based procurement can hasten industrial adoption throughout Europe while preserving technological sovereignty.

To sum up, this thesis helps close the gap between industrial application and quantum research. It provides an organized yet adaptable method to help businesses and policymakers navigate the uncertainties of quantum innovation by fusing theoretical contemplation, empirical understanding, and managerial design. The Quantum Adoption Pathway offers a useful road map for capability development, risk mitigation, and strategic alignment in addition to a conceptual framework, the following figure consolidates the proposed framework for quantum computing adoption.

Europe's place in the global quantum economy will depend on its ability to convert scientific advancements into economic and societal benefits as quantum technologies continue to advance. By transforming curiosity into strategy, experimentation into readiness, and innovation into competitive advantage, the work presented here seeks to facilitate that shift.

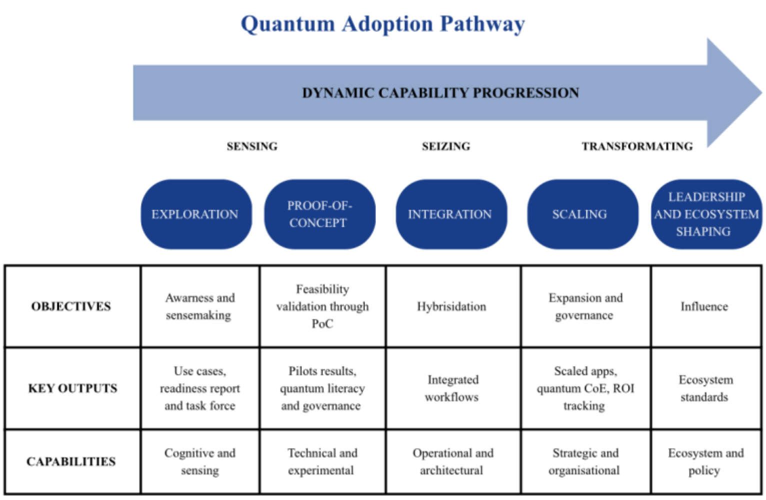

Figure 4.6: The Quantum Adoption Pathway

Bibliography

McKinsey. (2025). *Quantum Technology Monitor.*

(NIST), N. I. (2023). *Post-Quantum Cryptography Standardization Project.* U.S. Department of Commerce, Gaithersburg, MD.

(QuIC), Q. I. (2023). *Recommendations from the European Quantum Industry Consortium (QuIC) for the EU quantum strategy.* Brussels: Quantum Industry Consortium.

(WIPO), W. I. (2017). *Patents and the Fourth Industrial Revolution: The Inventions behind Digital Transformation.* Geneva: World Intellectual Property Organization.

Aaronson, S. (2025). *Majorana 1 and the Future of Topological Qubits*. Tratto il giorno 7 2025 da Shtetl-Optimized: https://scottaaronson.blog

Abdel-Kareem, M. (2025). *Norwegian Government Commits NOK 1.1 Billion ($100 Million USD) to National Quantum Technology Initiative*. Tratto da Quantum Computing Report: https://quantumcomputingreport.com/norwegian-government-commits-nok-1-1-billion-100-million-usd-to-national-quantum-technology-initiative/

Abourokbah, Mashat, & Salam. (2023). *Role of Absorptive Capacity, Digital Capability, Agility, and Resilience in Supply Chain Innovation Performance.*

Ajagekar, & You. (2019). Quantum computing for energy systems optimization: Challenges and opportunities. *Energy, 179*.

Ajagekar, & You. (2019). Quantum computing for energy systems optimization: Challenges and opportunities. *Energy*.

Ajagekar, & You. (2020). *Quantum computing for energy systems optimization: Challenges and opportunities.*

Albash, T., & Lidar, D. (2018). Adiabatic Quantum Computing. *Rev. Mod. Phys., 90*(1).

Alliance, Q. I. (2024). *Qblox, Partner profile*. Tratto da https://quantuminternetalliance.org/qblox/

Anonymous. (2025, 6). (F. Ciancetta, Intervistatore)

Anumolu, V. (2025, March 8). Fundamentals of Modern Quantum Computing: A Technical Overview. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology, II*(11), 669-683.

Aramon, M., Rosenberg, G., Valiante, E., Miyazawa, T., Tamura, H., & Katzgraber, H. G. (2019). Physics-Inspired Optimization for Quadratic Unconstrained Problems Using a Digital Annealer. *Frontiers in Physics, 7*, 48.

Arrazola, J. M., Bergholm, V., Brádler, K., Bromley, T. R., Collins, M. J., Dhand, I., . . . Lavoie. (2021). Quantum circuits with many photons on a programmable nanophotonic chip. *Nature, 591*, 54-60.

Arute, F., Arya, K., Babbush, R., Bacon, D., Bardin, J. C., Barends, R., . . . Du. (2019). Quantum supremacy using a programmable superconducting processor. *Nature, 574*, 505-510.

Austria E. of. (2025). *Quantum Science Austria – Bringing the Quantum Community in Austria Together*. Tratto da Austrian Embassy: https://www.austria.org/new-austrian-quantum-content/quantum-science-austria

Baiardi, Christandl, & Reiher. (2023). *QuantumComputingforMolecularBiology.*
Balamurugan, K. S., Sivakami, A., Mathankumar, M., Satya Prasad, Y. J., & Ahmad, I. (2024). An elementary review on basic principles and development of quantum comput. *Journal of Molecular Structure*.
Balamurugan, K. S., Sivakami, A., Mathankumar, M., Yalla Jnan Devi Satya, p., & Irfan, A. (2024, July 15). Quantum computing basics, applications and future perspectives. *Journal of Molecular Structure*(1308).
Baldazzi, A. S. (2025). *Four-qubit variational algorithms in silicon photonics with integrated entangled photon sources.* Quantum Inf .
Barends, R., K., & J., M. A. (2014, April 23). Superconducting quantum circuits at the surface code threshold for fault tolerance. *Nature*(508), 500-513 .
Bauer, Bravyi, Motta, & Chan. (2020). *Quantum algorithms for quantum chemistry and quantum materials science.*
Bauer, Bravyi, Motta, & Chan. (2020). *Quantum algorithms for quantum chemistry and quantum materials science.*
Bauer, Bravyi, Motta, & Chan. (2020). *Quantum Algorithms for Quantum Chemistry and Quantum Materials Science.*
BCG. (2024). *The Long-Term Forecast for Quantum Computing Still Looks Bright.*
Bender2014. (s.d.). *File:Grovers algorithm.svg*. Tratto da https://en.wikipedia.org/wiki/File:Grovers_algorithm.svg#file
Bergholm. (2022). *PennyLane: Automatic differentiation of hybrid quantum-classical computations.*
BETA. (2023). *IBM and E.ON explore energy grid optimization*. Tratto da BETA: https://www.openqase.com/case-study/ibm-eon-partnership-quantum-computing-energy-grid-optimisation
Bharti, K., Cervera-Lierta, A., Kyaw, T. H., Haug, T., Alperin-Lea, S., Anand, A., . . . Aspuru-Guzik, A. (2021). Noisy intermediate-scale quantum (NISQ) algorithms. *94*(1).
Bharti, K., Cervera-Lierta, A., Kyaw, T. H., Haug, T., Alperin-Lea, S., Anand, A., . . . Aspuru-Guzik, A. (2022). Noisy intermediate-scale quantum (NISQ) algorithms. *Rev. Mod. Phys., 94*(1).
BIS. (2025). *BIS Papers No 158 Quantum-readiness for the financial system: a roadmap.*
Bluvstein, D., Levine, H., Semeghini, G., Wang, T. T., Ebadi, S., Kalinowski, M., . . . Lukin, M. D. (2022). A quantum processor based on coherent transport of entangled atom arrays. *Nature, 604*, 451-456.
BMW. (2025). *Quantum Computing at the BMW Group*. Tratto da https://www.bmwgroup.com/en/news/general/2025/quantum-computing.html
Braunstein, S., & van Loock, P. (s.d.). Quantum information with continuous variables. *Rev. Mod. Phys.2005, 77*(2), 513-577.
BRIDGE Quantum call for projects 2025. (2025). Tratto da BRIDGE: https://www.bridge.ch/en/M0VBCBisNAzM6eHE/page/quantum-call-2025
Brixen, P. A. (2025). *Danish quantum research strengthens its leading position*. Tratto da DTU: https://www.dtu.dk/english/news/all-news/danish-quantum-research-strengthens-its-leading-position?id=04f5f714-b9ef-4a9d-9f68-9d3e9038e8a7&
Brown, K., Kim, J., & Monroe, C. (2016, February 9). Co-Designing a Scalable Quantum Computer with Trapped Atomic Ions. *Quantum information*(2).
Capgemini Research Institute. (2022). *Quantum technologies: How to prepare your organization for a quantum advantage now.*

Carreras, A., Casanova, D., & Orús, R. (2025). *Limitations of Quantum Hardware for Molecular Energy Estimation Using VQE.* Quantum Physics.

Choucair. (2024). *Living In A Material World: Quantum-Centric Supercomputing May Redefine Materials Science*. Tratto da QuantumInsider: https://thequantuminsider.com/2024/10/29/living-in-a-material-world-quantum-centric-supercomputing-may-redefine-materials-science/

Cirq. (2025). Tratto da https://pypi.org/project/cirq/

Cohen, & Levinthal. (1990). Absorptive Capacity: A New Perspective on Learning and Innovation.

Commission, E. (2022). *TRL Assessment Tool Guide.*

Council National Science and Technology. (2024). *NATIONAL QUANTUM INITIATIVE SUPPLEMENT TO THE PRESIDENT'S FY 2025 BUDGET.*

Cristofaro. (2022). *Organizational sensemaking: A systematic review and a co-evolutionary model.*

Danish e-Infrastructure Consortium. (2024). *LUMI-Q to strengthen pan-European quantum resources with new IQM quantum computer*. Tratto da https://dqc.dk/lumi-q-to-strengthen-pan-european-quantum-resources-with-new-iqm-quantum-computer/

DataCenterDynamics. (2024). *ORCA launches PT-2 photonic quantum computer*.

Deutsch, D. (1985, July 8). Quantum theory, the Church–Turing principle and the universal quantum computer. (400), 97-117.

DHL. (2025). *THE QUANTUM LEAP IN LOGISTICS*. Tratto da DHL: https://lot.dhl.com/quantum-leap-logistics/

DigitaleEurope. (2024). *QUANTUM project kicks off to develop and implement the health data quality label for the secondary use of health data in the EU*. Tratto da DIGITALEUROPE: https://www.digitaleurope.org/news/quantum-project-kicks-off-to-develop-and-implement-the-health-data-quality-label-for-the-secondary-use-of-health-data-in-the-eu/

Directorate-General, C. (2025). *The EU's plan to become a global leader in quantum by 2030*. Tratto da European Commission : https://commission.europa.eu/news-and-media/news/eus-plan-become-global-leader-quantum-2030-2025-07-02_en

ECB. (2024). *Financial Stability Review.*

EE Times Europe. (2021). *French president details €1.8B quantum plan*. Tratto da https://www.eetimes.eu/french-president-details-e1-8b-quantum-plan/

Egger, Gambella, Marecek, McFaddin, Mevissen, Raymond, . . . Yndurain. (2020). *Quantum Computing for Finance: State-of-the-Art and Future Prospects.*

EIF. (2025). *EIF invests €30 million in Quantum technologies and Deep physics with Quantonation II*. Tratto da EIF: https://www.eif.org/InvestEU/news/2025/eif-invests-eur30-million-in-quantum-technologies-and-deep-physics-with-quantonation-ii.htm?lang=-en

Elevate Quantum . (2024). *Overarching Narrative: U.S. EDA Tech Hubs Phase 2 Application.* Elevate Quantum Consortium.

Ernström, U. (2025). *The initiative driving Sweden's quantum revolution*. Tratto da Wallenberg: https://kaw.wallenberg.org/en/research/initiative-driving-swedens-quantum-revolution

EuroHPC JU. (2024). *EuroHPC JU signs hosting agreements for quantum computers in Luxembourg and in the Netherlands*. Tratto il giorno 2025 da https://www.eurohpc-ju.europa.eu/paving-way-eurohpc-ju-signs-hosting-agreements-quantum-computers-luxembourg-and-netherlands-2024-12-18_en

European Commission . (2025). *A Coordinated Implementation Roadmap for the Transition to Post-Quantum Cryptography.*

European Commission . (2025). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL Quantum Europe Strategy: Quantum Europe in a Changing World.*

European Commission. (2023). *European Commission.* Brussels: European Commission.

European Commission. (2025). *European Chips Act official website*. Tratto da https://www.european-chips-act.com

European Commission. (2025). *European Quantum Communication Infrastructure (EuroQCI)*. Tratto da https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci

European Commission. (2025). *Quantum Europe Strategy*. Tratto da https://digital-strategy.ec.europa.eu/en/library/quantum-europe-strategy

Ezratty, O. (2022). *Understanding Quantum Technologies* (Vol. 4th). Editions Quantum.

Fadilpašić, S. (2025). *Forget ransomware - most firms think quantum computing is the biggest security risk to come*. Tratto da TechRadar: https://www.techradar.com/pro/security/forget-ransomware-most-firms-think-quantum-computing-is-the-biggest-security-risk-to-come

Farhi, Goldstone, & Gutmann. (2014). *A Quantum Approximate Optimization Algorithm.*

Federal Ministry of Education and Research, (. (2024). *Action concept on quantum technologies.* Tratto da https://www.bmftr.bund.de/SharedDocs/Downloads/DE/2024/2024-12-11-handlungskonzept-quantentechnologie-en.pdf?__blob=publicationFile&v=2

Feniou, C., Hassan, M., & Claudon, B. e. (2025). *Greedy gradient-free adaptive variational quantum algorithms on a noisy intermediate scale quantum computer.* Sci Rep.

Feynman, R. (1982, June). Simulating physics with computers. *International Journal of Theoretical Physics*(21), 467-488.

Firth. (2025). *The Logistics Trend Map - Exploring 2025's global logistics trends*. Tratto da Maersk: https://www.maersk.com/insights/integrated-logistics/2025/03/27/logistics-trend-map-exploring-global-logistics-trends-2025

Flöther. (2023). *The state of quantum computing applications in health and medicine.*

Flagship, Q. (2025). *Quantum Flagship official website*. Tratto il giorno 2025 da https://qt.eu/

Frąckiewicz. (2025). *SALTO QUANTICO: PERCHÉ LE AZIONI DI IONQ, RIGETTI E D-WAVE STANNO VOLANDO IN UNA RIVOLUZIONE TECNOLOGICA*. Tratto da ts2: https://ts2.tech/it/salto-quantico-perche-le-azioni-di-ionq-rigetti-e-d-wave-stanno-volando-in-una-rivoluzione-tecnologica/

Gamel, O. (2016). Entangled Bloch Spheres: Bloch Matrix and Two Qubit State Space. *Phys. Rev. A, 93*.

GAO. (2021).

General Secretariat, C. (2025). *AOB for the meeting of the Transport, Telecommunications and Energy Council on 6 June 2025 : Spain's Quantum Technologies Strategy (2025- 2030).*
Government of France. (2025). *Plan Quantique – France 2030*. Tratto da https://quantique.france2030.gouv.fr
Government, T. D. (2023). *National Strategy for Quantum Technology.*
Groenewgen. (2024). *China's long view on quantum tech has the US and EU playing catch-up .*
Gupta, Wood, Engstrom, Pole, & Shrapnel. (2025). *A systematic review of quantum machine learning for digital health.*
Harnessing our quantum potential – towards a Norwegian quantum strategy. (2025). Tratto da Regjeringen: https://www.regjeringen.no/no/aktuelt/harnessing-our-quantum-potential-towards-a-norwegian-quantum-strategy/id3103651/
Hartmut, N. (2024). *Meet Willow, our state-of-the-art quantum chip*. Tratto da Blog Google: https://blog.google/technology/research/google-willow-quantum-chip/
Harvest now, decrypt later attacks & how they relate to the quantum threat. (2025). Tratto da Sectigo: https://www.sectigo.com/resource-library/harvest-now-decrypt-later-quantum-threat
Huang, H.-L., Wu, D., Fan, D., & Zhu, X. (2020, November 2). Superconducting Quantum Computing: A Review. *Science China Information Sciences*.
IBM. (2025). *IBM Quantum documentation* . Tratto da https://quantum.cloud.ibm.com/docs/it
IBM. (2025). *IBM Quantum Roadmap*. Tratto da https://www.ibm.com/roadmaps/quantum/2025/
Intesa San Paolo. (2022). Tratto da https://group.intesasanpaolo.com/it/newsroom/comunicati-stampa/2022/05/intesa-sanpaolo-investe-nel-quantum-computing--con-neva-sgr-e-il#
IQM. (2025). *IQM Quantum Computers Raises over $300 Million in Series B Funding Round Led by U.S. Investor Ten Eleven Ventures with strong support from Tesi*. Tratto da IQM: https://meetiqm.com/press-releases/iqm-quantum-computers-raises-over-300-million-in-series-b-funding-round/
IQM Quantum Computers. (2024). *IQM Quantum Computers reaches production milestone of 30 quantum computers*. Tratto da https://meetiqm.com/press-releases/iqm-quantum-computers-reaches-production-milestone-of-30-quantum-computers/
IQM, Q. C. (2025). *IQM Quantum Computers*. Tratto da https://meetiqm.com
Jenkins, J., Berente, N., & Angst, C. (2022). The quantum computing business ecosystem and firm strategies. *Proceedings of the 55th Hawaii International Conference on System Sciences*, (p. 6432–6441).
Jenkins, J., Berente, N., & Angst, C. (2022). *The Quantum Computing Business Ecosystem and Firm Strategies.*
Jeremy, L., O'Brien, Furusawa, A., & Vučković, J. (2009). Photonic quantum technologies. *Nature Photonics, 3*(12), 687-965.
Jiao, Du, Shi, Hou, & Gui. (2021). *Dynamic Absorptive Capability and Innovation Performance: Evidence from Chinese Cities.*
JU, C. (2024). *Chips JU: first calls for quantum chip pilot lines announced*. Tratto da Quantum Flagship: https://qt.eu/news/2024/2024-09-11_chips-ju-first-calls-for-quantum-chip-pilot-lines-announced

Kadowaki, T., & Nishimori, H. (1998). Quantum Annealing in the Transverse Ising Model. *Phys. Rev. E, 58*.

Karzig, T., Knapp, C., Lutchyn, R. M., Bonderson, P., Hastings, M. B., Nayak, C., . . . Freedman, M. H. (2017). Scalable Designs for Quasiparticle-Poisoning-Protected Topological Quantum Computation with Majorana Zero Modes. *Phys. Rev. B, 95*(23).

Kerstens, & Langley. (2025). An innovation intermediary's role in enhancing absorptive capacity for cross-industry digital innovation: Introducing an awareness capability and new intermediary practices. *Journal of Business Research*.

King, J., Yarkoni, S., Raymond, J., Ozfidan, I., King, A. D., Nevisi, M. M., . . . McGeoch, C. C. (2019). Quantum Annealing amid Local Ruggedness and Global Frustration. *Nature Communications , 12*.

Kleja. (2025). *Danish quantum investment will boost EU biotech and medical research*. Tratto da EURACTIV: https://www.euractiv.com/news/danish-quantum-investment-will-boost-eu-biotech-and-medical-research/

Knill, E., Laflamme, R., & Milburn, G. (2001). Efficient Linear Optics Quantum Computation. *Nature, 409*(6816), 46-52.

Koch, J., Terri M., Y., Gambetta, J., Houck, A., Schuster, D., Majer, J., . . . Schoelkopf, R. (2007, September 26). Charge insensitive qubit design derived from the Cooper pair box. *Physical Review A*(4).

Kreft. (2025). *When Quantum Computing Meets Supply Chain Management*. Tratto da lingaro: https://lingarogroup.com/blog/when-quantum-computing-meets-supply-chain-management

Lanes, O., Beji, M., Corcoles, A. D., Dalyac, C., Gambetta, J. M., Henriet, L., . . . Pero. (2025). A Framework for Quantum Advantage.

Lavado, Fernandez, Vlaisavljevic, & Medina. (2023). Cross-industry innovation: A systematic literature review.

Leibfried, D., Blatt, R., Monroe, C., & Wineland, D. (2003, March 10). Quantum dynamics of single trapped ions. *Reviews of Modern Physics*(75), 281-324.

Lemo, Saber, Kundur, & Skorek. (2025). *Potential of Quantum Computing Applications for Smart Grid Digital Twins and Future Directions.*

Levine, H., Keesling, A., Semeghini, G., Omran, A., Wang, T. T., Ebadi, S., . . . Lukin, M. D. (2019). Parallel implementation of high-fidelity multi-qubit gates with neutral atoms. *Phys. Rev. Lett., 123*(17).

Li, W., Zhang, S.-X., Sheng, Z., Gong, C., Chen, J., & & Shuai, Z. (2025). *Quantum machine learning of molecular energies with hybrid quantum-neural wavefunction.*

Liu, Li, & Yang. (2024). *Perturbative variational quantum algorithms for material simulations.*

Loss, D. (., & DiVincenzo, D. P. (1998). Quantum Computation with Quantum Dots. *Phys. Rev. A, 57*(1), 120-126.

McKinsey, &. C. (2025). *Quantum Monitor 2025.* McKinsey & Company.

Meng-Leong, H., & Sin-Mei, C. (2023, November 9). Business Renaissance: Opportunities and Challenges at the Dawn of the Quantum Computing Era. *Global Perspectives on the Opportunities and Future Directions of Businesses*, 585-565.

Microsoft Quantum. (2025). *Azur Quantum documentation* . Tratto da https://learn.microsoft.com/en-us/azure/quantum/

Monroe, C., & Kim, J. (2013, March 8). Scaling the ion trap quantum processor. *Science*, 1164-1169.
Mosca. (2022). *Quantum threat timeline* .
Multiverse Computing . (2023). *Crédit Agricole tests quantum in finance.*
N.d. (s.d.). *ResearchGate*. Tratto da https://www.researchgate.net/figure/On-the-three-dimensional-Bloch-sphere-with-x-y-and-z-axes-the-north-and-south-poles_fig5_301703361/actions#reference
N.d. (s.d.). *ResearchGate*. Tratto da https://www.researchgate.net/figure/Schematic-of-a-Transmon-qubit-and-its-effective-circuit-a-The-effective-circuit-model_fig2_342301953
Natalucci, M. (2025, February 4). *Osservatori.net*. Tratto da Osservatori.net digital innovation: https://www.osservatori.net/blog/quantum-computing/quantum-computing-significato/
Nayak, C., Simon, S. H., Stern, A., Freedman, M., & Das Sarma, S. (2008). Non-Abelian Anyons and Topological Quantum Computation. *Rev. Mod. Phys., 80*, 1083.
NEWS, Q. (2024). *Quantum Computing in Energy: Quantum-assisted grid optimization*. Tratto da Quantum zeitgeist: https://quantumzeitgeist.com/quantum-computing-in-energy-quantum-assisted-grid-optimization/
Nielsen, M. A., & Chuang, L. I. (2010). *Quantum Computation and Quantum Information.* Cambridge Univerity Press.
Nilchiani, R., Caddell, J., & Taramsari, H. (2025). The Extended Technology Readiness Level (eTRL): From Deployment to Obsolescence. *IEEE Open Journal of the Systems Engineering, 3*, 25.
NIST. (2024). *NIST*. Tratto da NIST: https://www.nist.gov/news-events/news/2024/08/nist-releases-first-3-finalized-post-quantum-encryption-standards
NQCC. (2025). *Quantum Computing Use Case Compendium.*
NQCC. (2025). *Quantum Computing Use Case Compendium.*
OECD. (2025). *A quantum technologies policy primer.* Paris: A quantum technologies policy primer.
OECD. (2025). *A QUANTUM TECHNOLOGIES POLICY PRIMER.*
ORCA, C. (2024). *ORCA Computing* . Tratto da https://orcacomputing.com
Osaba, Delgado, Ali, Miranda-Rodriguez, Leceta, d., & Rivas. (2025). *Quantum Computing in Industrial Environments: Where Do We Stand and Where Are We Headed?*
OTI Lumionics. (2025). *Enabling quantum computing for materials discovery.* Tratto da OTI: https://otilumionics.com/quantum-computing/
Pan, F., Chen, K., & Zhang, P. (2022). Solving the sampling problem of the Sycamore quantum circuits. *Physical Review Letters , 129*.
Pasqal. (2025). *Pasqal Cloud Service*. Tratto da https://docs.pasqal.com/cloud/
Pasqal. (2025). *Pasqal, Neutral atom quantum computing*. Tratto da https://www.pasqal.com
Phillipson. (2025). *Quantum Computing in Logistics and Supply Chain Management - an Overview.*
Phillipson. (2025). *Quantum Computing in Logistics and Supply Chain Management an Overview.*

Poindexter, O. (2025). *Breaking Ground in Quantum Computing: QSA's Trapped-Ion Advances*. Tratto da Quantum System Accelerator: https://quantumsystemsaccelerator.org/2025/06/10/trapped-ions/

Poznań Supercomputing and Networking Center (PSNC). (2025). *EuroQHPC-Integration: The six hosting entities of the EuroHPC quantum computers kick off a joint integration project in Krakow*. Tratto da https://www.psnc.pl/euroqhpc-integration-the-six-hosting-entities-of-the-eurohpc-quantum-computers-kick-off-a-joint-integration-project-in-krakow/

Preskill. (2018). *Quantum Computing in the NISQ era and beyond.*

Preskill. (2018). *Quantum Computing in the NISQ era and beyond.*

Preskill, J. (1998). Lecture Notes for Ph ysics Quan tum Information and Computation.

Preskill, J. (2018, August 6). Quantum Computing in the NISQ era and beyond. *Quantum the open journal for quantum science*(2), 79.

Preskill, J. (2018). *Quantum Computing in the NISQ era and beyond.*

Purohit, A., Kaur, M., Seskir, Posner, & Venegas-Gomez. (2023). *Building a quantum-ready ecosystem.*

Purohit, A., Kaur, M., Seskir, Z. C., Posner, M. T., & Venegas-Gomez, A. (2023). Building a Quantum-ready Ecosystem. *IET Quantum Communications, 4*(1), 11-24.

Qblox. (2025). *Qblox, Quantum control systems*. Tratto da https://www.qblox.com

Quandela. (2025). *Quandela* . Tratto da https://www.quandela.com

Quantinuum . (2025). *Mitsui, QSimulate, and Quantinuum Launch "QIDO": A Quantum-Integrated Chemistry Platform Targeting Faster Drug and Materials Discovery*. Tratto da Quantinuum : https://www.quantinuum.com/press-releases/mitsui-qsimulate-and-quantinuum-launch-qido-a-quantum-integrated-chemistry-platform-targeting-faster-drug-and-materials-discovery

Quantinuum. (2025). *Quantinuum Dominates the Quantum Landscape: New World-Record in Quantum Volume*. Tratto da https://www.quantinuum.com/blog/quantum-volume-milestone

Quantinuum. (2025). *Quantinuum Technical Documentation* . Tratto da https://docs.quantinuum.com

Quantum Austria. (2024). Tratto da Austrian Science Fund: https://www.fwf.ac.at/en/funding/portfolio/subject-specific-funding/quantum-austria

Quantum Computing Report. (2024). *Quandela Launches Belenos Photonic Quantum Computer with Doubling of Qubit Count and 4,000× Power Increase*.

Quantum Delta NL. (2023). *Quantum Delta NL expands strategy with renewed National Growth Fund support*. Tratto da https://quantumdelta.nl/news/quantum-delta-nl-expands-strategy-with-renewed-national-growth-fund-support

Quantum Flagship. (2024). *Competence Framework for Quantum Technologies (Version 2.5).* Tratto da https://qt.eu/media/pdf/Competence_Framework_for_QT_v2_5_2024.pdf

Quantum Industry Consortium. (2025). *QuIC Quantum Industry Consortium official website*. Tratto da https://www.euroquic.org

QuantumWare. (2025). *QuantWare, Superconducting quantum processors*. Tratto da https://www.quantware.com

QuEra. (2025). *QuEra Computing Completes $230M Financing to Accelerate Development of Large-Scale Fault-Tolerant Quantum Computers*. Tratto da QuEra: https://www.quera.com/press-releases/quera-computing-completes-230m-financing-to-accelerate-development-of-large-scale-fault-tolerant-quantum-computers

QuIC. (2025). *QuIC Position Paper on the Quantum Europe Strategy.*

Qunasys. (2025). *QunaSys Joins a Leading European Consortium to Advance Sustainable Battery Innovation with Quantum Computing*. Tratto da Qunasys: https://qunasys.com/en/news/posts/fullmap_en/

Reuters. (2024). *Germany aims to be world leader in quantum technologies, says Scholz*. Tratto da Reuters: https://www.reuters.com/technology/germany-aims-be-world-leader-quantum-technologies-says-scholz-2024-10-01/

Reuters. (2024). *Germany aims to be world leader in quantum technologies, says Scholz*. Tratto da Reuters: https://www.reuters.com/technology/germany-aims-be-world-leader-quantum-technologies-says-scholz-2024-10-01/

Reuters. (2025). *Quantum computing startup QuEra closes $230 million funding round*. Tratto da Reuters: https://www.reuters.com/technology/quantum-computing-startup-quera-closes-230-million-funding-round-2025-02-11/

Riverlane. (2024). *Quantum Error Correction Report 2024.*

Riverlane. (2025). *Riverlane , The Operating System for Quantum Computers*. Tratto da https://www.riverlane.com

Saffman, M., Walker, T., & Molmer, K. (2010). Quantum information with Rydberg atoms. *Rev. Mod. Phys., 82*(3), 2313-2363.

Sancho-Zamora, Hernández-Perlines, Peña-García, & Gutiérrez-Broncano. (2022). The Impact of Absorptive Capacity on Innovation: The Mediating Role of Organizational Learning. *International Journal of Environmental Research and Public Health*.

Sectigo. (2025). *Harvest now, decrypt later attacks & how they relate to the quantum threat*. Tratto da Sectigo: https://www.sectigo.com/resource-library/harvest-now-decrypt-later-quantum-threat

Shamsuddoha, Kashem, Nasir, Hossain, & Ahmed. (2025). *Quantum Computing Applications in Supply Chain Information and Optimization: Future Scenarios and Opportunities.*

Sivakumar, Nair, Joshi, Wesley, Videsh, & Reena. (2024). *A computational study and analysis of Variational Quantum Eigensolver over multiple parameters for molecules and ions.*

Swayne. (2025). *Amazon Braket Speeds Quantum Research With New Batch Processing Feature*. Tratto da QuantumInsider: https://thequantuminsider.com/2025/08/15/amazon-braket-speeds-quantum-research-with-new-batch-processing-feature/

Swayne, M. (2024). *National, Quantum Computing Business, Research*. Tratto da Quantum Insider : https://thequantuminsider.com/2024/12/04/senators-quantum-leaders-back-2-7-billion-national-quantum-initiative-reauthorization-act/

Swayne, M. (2025). *Qunova Algorithm Delivers Modeling Of Large, Complex Molecules*. Tratto da Quantum Insider: https://thequantuminsider.com/2025/03/24/now-on-ibms-qiskit-functions-catalog-qunova-algorithm-delivers-modeling-of-large-complex-molecules/

Swayne, M. (s.d.). *Quantum Insider* .

SwissQuantum. (2025). *Swiss Quantum Initiative*. Tratto da SQI: https://www.sbfi.admin.ch/en/swiss-quantum-initiative-en

techUK. (2025). *https://www.techuk.org/resource/eu-launches-quantum-strategy.html*. Tratto da https://www.techuk.org/resource/eu-launches-quantum-strategy.html

The Government of Spain launches Spain's first Quantum Technologies Strategy with an investment of €800 million. (2025). Tratto da LaMoncloa: https://www.lamoncloa.gob.es/lang/en/gobierno/news/paginas/2025/20250424-quantum-technologies-strategy.aspx

The Quantum Insider. (2024). *Pasqal reports loading more than 1000 atoms in quantum processor*. Tratto da https://thequantuminsider.com/2024/06/25/pasqal-reports-loading-more-than-1000-atoms-in-quantum-processor/

University of California. (2025, 2 20). *New State of Matter Achieved in Microsoft's Majorana 1 Quantum Prototype*. Tratto il giorno 7 2025 da https://www.universityofcalifornia.edu/news/we-have-created-new-state-matter-new-topological-quantum-processor-marks-breakthrough

Veldhorst, M., Hwang, J. C., Yang, C. H., Leenstra, A. W., de Ronde, B., Dehollain, J. P., . . . Dzurak, A. S. (2014). An addressable quantum dot qubit with fault-tolerant control fidelity. *Nature Nanotechnology , 9*(12), 981-985.

Vinnova finances a Swedish platform for quantum technology. (2023). Tratto da Vinnova: https://www.vinnova.se/en/news/2023/11/vinnova-finances-a-swedish-platform-for-quantum-technology

Weinberg, A. I. (2025). *Preparing for the Post Quantum Era: Quantum Ready Architecture for Security and Risk Management (QUASAR) -- A Strategic Framework for Cybersecurity.*

Wie, C. R. (2020, August 3). Two-Qubit Bloch Sphere. *Quantum Physics*(2), 383-396.

Woollacott, E. (2025). *Post-quantum cryptography is now top of mind for cybersecurity leaders*. Tratto da ITPro: https://www.itpro.com/business/post-quantum-cryptography-is-now-top-of-mind-for-cybersecurity-leaders

World Economic Forum . (2022). *Quantum Computing Governance Principles.*

World Economic Forum . (2024). *Quantum economy blueprint.* Geneva: World Economic Forum.

World Economic Forum. (2022). *State of Quantum Computing: Building a Quantum Economy.*

Wrzosinski. (2025). *Quantum Healthcare in Europe: Funding, Regulation and the Path to Market*. Tratto da disrupting.healthcare: https://disrupting.healthcare/2025/09/10/quantum-healthcare-in-europe-funding-regulation-and-the-path-to-market/

Zhong, H.-S., Wang, H., Deng, Y.-H., Chen, M.-C., Peng, L.-C., Luo, Y.-H., . . . Pan, J.-W. (2020). Quantum computational advantage using photons. *Science, 370*(6523), 1460-1463.

Zlokapa, A., Villalonga, B., Boixo, S., & Lidar, D. A. (2023). Boundaries of quantum supremacy via random circuit sampling. *Nature Quantum Information*.