Strategic Research and Industry Agenda

QUANTUM FLAGSHIP

Strategic Research and Industry Agenda

European Commission

QUANTUM FLAGSHIP

The European Quantum Flagship has received financial support by the European Commission in the scope of the Coordination and Support Action “QUCATS” (Grant Number 101070193).

Realized by the CSA QUCATS
https://qt.eu/about-quantum-flagship/projects/qucats/

CSA project coordinator
CNRS, 3 rue Michel Ange, F75794 Paris
Phone: +331 64 53 33 78

Twitter: **twitter.com/QuantumFlagship**
LinkedIn: **www.linkedin.com/company/quantum-flagship/**

Published in February 2024 by the European Quantum Flagship under the supervision of the Strategic Advisory Board
https://qt.eu/structure-governance/strategic-advisory-board

SRIA Coordinator: Salvatore Cinà (CEA)

SRIA Core Team: Philippe Grangier (CNRS), Antonio Acín (ICFO), Raja Yehia (ICFO), Ziyad Amodjee (CNRS)

SRIA Working Group Leaders
Salvatore Cinà (CEA), Quantum Computing and Quantum Simulation
Antonio Acín (ICFO) and Raja Yehia (ICFO), Quantum Communications
Pekka Pursula (VTT), Quantum Sensing & Metrology
Antonio Acín (ICFO) and Raja Yehia (ICFO), Basic Quantum Science
Gabriele Bulgarini (TNO), Engineering & Enabling technologies
Jacob Sherson (Aarhus Univ.), Education & Workforce Development
Florent Staley (CEA), Standardisation & Benchmarking
Thierry Botter (QuIC) and Markus Wilkens (VDI), Funding: Private & Public
Jari Rantala (VTT), Intellectual Property Rights
Caroline Sevin (CEA) and Thierry Botter (QuIC), International Collaboration & Export Control Regulation
Lydia Sanmarti (ICFO), Social and ethical values
Chaymae Senhaji (CEA), Communications & Outreach
Philippe Chomaz (CEA), Governance

EuroHPC-QCS links: Laura Schulz (LRZ) and Kristel Michielsen (Forschungszentrum Jülich)
EuroQCI link: Felix Wissel (Deutsche Telekom)

SRIA 2030: Roadmap and Quantum Ambitions over this Decade

The document presents the full updated Strategic Research and Industry Agenda (SRIA 2030) for Quantum Technologies (QT) in the European Union (EU).

It follows a preliminary document published in November 2022, with the goal of aligning the Strategic Research Agenda (SRA, published in 2020), which articulates the European Research Community's vision for QT, and the preliminary Strategic Industry Roadmap (SIR) published by the European Quantum Industry Consortium (QuIC) in 2022, conveying the vision of the EU industrial community. Furthermore, this preliminary document provided more specific recommendations regarding the integration of QT into the work programs of the Chips-Act for semiconductors, and EuroHPC for High-Performance Computing (HPC).

The SRIA 2030 refines the initial document, offering a roadmap for concrete actions that can be undertaken in collaboration with all QT initiatives within the EU. Building upon the November 2022 version, the document has been updated and significantly enhanced, considering a large number of additional contributions, including:

- The updated SIR published by QuIC in 2023.
- Contributions from thematic working groups set up by the Coordination and Support Action QUCATS.
- Input from all governance bodies within the quantum flagship (https://qt.eu/structure-governance/).
- Contributions from the major quantum initiatives within the EU, including EuroHPC-QCS and EuroQCI.

The SRIA 2030 is designed as the reference document that harmonizes the roadmaps and objectives of both the scientific and industrial communities. This inclusiveness extends beyond the quantum community, to include those who plan to integrate quantum technologies into their products and services, each with its distinct application and requirements. This comprises: the HPC industry, who will be exploiting the quantum hardware as an accelerator in their infrastructures; the communication industry, who will use quantum technologies to strengthen the security and capabilities of their future networks; the semiconductor industry, who is taking into account the requirement of pilot and productions lines for quantum technologies in their roadmap via the Chips Act.

Structure

The SRIA 2030 comprises two main parts. Part 1 focuses on the usual four pillars of QT: quantum computing, quantum simulation, quantum communication, and quantum sensing and metrology.

Each chapter follows a similar structure, commencing with a discussion on the impact, societal challenges, and quantum opportunities associated with the technology. Subsequently, the document addresses the primary challenges, whether they are scientific, technological, or industrial. It then outlines actions to address these challenges, offering a clear strategy and roadmap. Each chapter concludes with specific objectives and recommendations.
A dedicated chapter consolidates recommendations that are relevant across all pillars, as concepts, tools, and technologies developed in one pillar may have applications in others. For example, advancements in quantum communications can support the design of quantum sensor networks or distributed quantum computing protocols. Techniques for efficient quantum information processing may also find application in quantum repeaters for long-distance quantum communication.

Part 2 covers transverse issues related to quantum technologies, encompassing basic science, engineering, and enabling technologies that cut across the four pillars. It addresses the need to enhance education and training to ensure the community has the skilled workforce necessary for successful implementation. Furthermore, it offers recommendations to bolster the EU's role in standards and benchmarking while strengthening intellectual property protection. It also outlines an agenda for enhancing international collaborations and improving the EU's funding model, both in the private and public sectors. It presents proposals for broadening participation from under-represented countries and ensuring equality, diversity, and inclusion within the quantum community. Communication and outreach play a pivotal role in sharing the future impact of quantum technologies, inspiring and expanding the community, while effective governance facilitates the efficient operation of this transverse community.

Methodology

In this section, we give details on the methodology employed to gather, include, and harmonize all the contributions in the SRIA 2030. Prior to its deployment, this methodology has been validated by the Strategic Advisory Board (SAB) of the Quantum Flagship.

The contributions to the SRIA were collected through several rounds of consultations.

The first consultation occurred between January and May 2023, primarily involving the Working Groups (WGs) initially formed to develop the SRA. The first step, carried out by the CSA QUCATS, involved renewing and expanding the WGs through consultation with all governing bodies of the quantum flagship. Clear interfaces were established to coordinate contributions from other initiatives within the EU. After a series of iterations, the initial list of WG members was formed, featuring experts from academia and industry, each chapter led by a designated WG leader.

The first consultation took place using a restructured version of the SRIA published in November 2022 as the starting document. Contributions from WG members were consolidated by WG leaders, and all chapters were merged into a preliminary draft of the SRIA 2030.

The second, broader consultation was carried out between July and September 2023, involving all key stakeholders in the EU, including the Quantum Coordination Board (QCB), the Quantum Community Network (QCN), the SAB, QuIC, the Directorate-General for Communications Network, Content and Technology (DG CNECT), the WGs, EuroHPC-QCS, and EuroQCI. The first draft of the SRIA 2030 was distributed to hundreds of experts across the EU through these channels, resulting in contributions of more than 300 experts during this second consultation. The consultation via the QCN allowed for the contribution and the coordination of the EU member states, via the National Representatives, while the QCB made sure the SRIA also included the contribution from the Quantum Flagship project coordinators and project coordinators from other EC programs.

Contributions from this phase were initially consolidated by the WG leaders, and all chapters were merged into the second draft of the SRIA 2030. In October 2023, the document was presented to the SAB for recommendations, and shared with the quantum community during a panel session at the European Quantum Technology Conference (EQTC) in Hannover. After incorporating the feedback from the SAB, the SRIA 2030 assumed its final format, endorsed by the SAB, and was delivered to the European Commission in digital form in December 2023.

Executive Summary

The present Strategic Research and Industry Agenda (SRIA) document is a EU-wide Strategic Plan concerning Quantum Technologies (QT) in Europe. QT represent an emerging global strategic domain poised to revolutionize technological capabilities, with the promise to address pressing contemporary challenges, such as drug and material discovery, energy generation and storage, cyber infrastructure protection or subsurface resource detection. The document is structured along four vertical pillars on quantum computation, simulation, communication, and sensing and metrology, and many different transversal topics common to all of them, ranging from basic science and enabling technologies to education, communication, standards or intellectual property.
In the last years, global competition in quantum technologies is fiercely intensifying. And while the European Union (EU) currently shows the highest level of public funding, fuelling world-leading research and expertise in quantum technologies, European innovators and industries have not yet fully capitalized on this potential
To secure a position of global leadership, safeguard strategic interests, ensure autonomy, bolster security, and avoid technological dependence on third-party nations, the EU must therefore establish an independent capacity for quantum technology development and production. This effort must aim to bridge the transition from laboratory to mass production, creating a world-leading ecosystem supporting a broad array of scientific and industrial applications.
To realize this vision and compete on the global stage, collaboration and investments beyond the EU's singular capabilities or any individual Member State are imperative. Collective action, uniting Member States and the European Commission, is vital to accelerate excellence in quantum technologies at European, national, and regional levels. This collaborative approach will enhance awareness of the economic and societal potential of quantum technologies, strengthening the EU's role as a global player in this transformative field, and thereby positioning the Union as the world's "Quantum Valley".
The purpose of the present SRIA is both to survey the current state of the art, and to put forward directions and recommendations for the future.

Structure of the document

This complex landscape is reflected in structure of the present SRIA document, which provides a comprehensive exploration of quantum technologies, their challenges and opportunities, and their potential societal impact. It offers a detailed examination of various facets of quantum technology, providing recommendations and insights into how the European quantum ecosystem can evolve and adapt to this rapidly advancing field.

Its structure can be summarized as follows:

- *Quantum Computing:* This section delves into quantum computing, discussing its societal impact, challenges, and opportunities. It covers topics such as the quantum computation stack, qubits, qubit control, software stack, quantum operating systems, quantum algorithms, and more. Objectives and recommendations for quantum computation are also addressed.
- *Quantum Simulation:* This section focuses on quantum simulation, examining its impact, challenges, and opportunities. It covers physical platforms, qubit control, quantum APIs, quantum algorithms, It includes a hybrid HPC-quantum computing section, shared with Quantum Computing, discussing the European Pilot <HPC|QS> and other related initiatives.
- *Quantum Communication:* This section explores impact, societal challenges, and opportunities of this technology, including point-to-point networks, the Quantum Internet, and use cases. It also addresses hardware and software challenges as well as the EuroQCI initiative.
- *Quantum Sensing & Metrology:* This section discusses quantum sensing and metrology, their societal impact, and applications in areas like biology, positioning, navigation, and timing.

It also covers scientific, technological, and industrial challenges, as well as objectives and recommendations.

- *General Recommendations:* This section provides overarching recommendations related to hardware, software, and other aspects that apply across the four pillars of quantum technology.
- *Quantum Resources, Innovation, Industrialisation, and Societal Impact:* This broad section covers various aspects, including basic quantum science, engineering, enabling technologies, education, standardization, funding, intellectual property rights, international collaboration, social and ethical values, communications and outreach. The document concludes with a section on governance, discussing principles, the current Quantum Flagship Governance structure, and the evolving European quantum ecosystem.

Coordination and Synergies with the current EU landscape

The Flagship's ramp-up phase (2018-2022) has established a solid foundation for its ongoing second phase. This new phase maintains its commitment to advancing promising Quantum Technologies across the four vertical pillars (computation, simulation, communication, and sensing/metrology), push forward innovative technologies and continues to drive progress in quantum fundamental science, a catalyst for established quantum technology evolution and innovation.

Several vital infrastructures have been initiated, within the Horizon Europe and Digital Europe programs:

- The European Quantum Computing and Simulation Infrastructure (EuroHPC-QCS) which aims to integrate Flagship's quantum computers and simulators into the Union's High-Performance Computing (HPC) infrastructure, playing a pivotal role in future HPC with post-exascale, energy-efficient computing technologies.
  Chapters 1.1 and 1.2 provide a clear strategy and recommendations to develop quantum computing and simulator (QCS) devices that outperform or accelerate existing classical computers, to solve specific problems relevant for industry, science and technologies. Exploiting their full potential requires integration into classical computing. Section 1.2.D, developed with EuroHPC-QCS, translates these recommendations into how QCS can integrate into the HPC system that perform the non-quantum computing tasks in the hybrid HPC-QCS infrastructure. QCS can then accelerate solutions to key problems, while running in concert with existing, established, and widely used classical algorithms and applications.
- The European Quantum Communication Infrastructure (EuroQCI), which aims to create a secure quantum communication network spanning the entire EU and its overseas territories. Chapter 1.3 defines the EU strategy to develop a Europe-wide quantum network that complements and expands the current digital infrastructure, laying the foundations and providing technological advances for a Quantum Internet, while focusing the technological recommendations on the implementation of a secure communication networks, enabling applications such as quantum key distribution (QKD).
  The technological implementation, and the corresponding recommendations, are further defined in Section 1.3.D, developed with EuroQCI. Its focus is on the deployment of the different stages, from the feasibility evaluation of EuroQCI, through the in-depth studies on overarching architectures both for terrestrial and space segments, to its final deployment.
- The Chips for Europe initiative has been developed to provide advanced technology and engineering capabilities, including specialized clean rooms, prototyping and production foundries, and testing facilities. This initiative will be essential to enable miniaturization, integration, reliability, and mass-market adoption of quantum devices.
  Chapter 2.2 focuses on the engineering and the technologies required for the implementations and operations of quantum technologies. In alignment with the Chips Act, it covers the requirements for manufacturing, testing & packaging facilities, focusing the strategy and the

recommendations on both technologies for dedicated quantum chips, as well as the enabling technologies, i.e. classical chips for quantum.
It also aligns the roadmaps of the ongoing initiatives (Qu-Pilot and Qu-Test) with the future investments foreseen in the Chips Act.

Within the same timeframe, the European quantum ecosystem has also experienced significant growth:

- The Quantum Industry Consortium (QuIC) has been formed with the mission of enhancing the competitive edge and economic expansion of the European quantum technology industry. QuIC aims to generate value across the continent and build a robust EU ecosystem encompassing Small and Medium-sized Enterprises (SMEs), major corporations, investors, and leading researchers.
- National Quantum Initiatives have emerged across EU27 countries and significant resources have been invested in advancing the Flagship's verticals, and corresponding enabling sciences and technologies, training, and innovation. Overall, currently this corresponds to a total investment in excess of 5.7 billion Euro over a period of 5 years.
- Complementary activities have been launched, including: the European Innovation Council (EIC) Pathfinder Challenge, the QuantERA program, a network of 39 leading European Research Funding Organizations, and support from top-down funding opportunities, such as the European Research Council (ERC), Marie Skłodowska-Curie Actions, and the European Metrology Programme for Innovation and Research (EMPIR).
  As presented in the methodology section, thanks to the process used for building the SRIA, the full EU quantum ecosystem has been consulted, ensuring that the recommandations in the different chapters are aligned with the strategies of the main EU stakeholders.

Recommended actions

Within the Flagship, results from basic research are developed into concrete technology deliverables in all areas tacking into account dependencies from international suppliers of critical components. The Chips for Europe initiative will create the necessary capabilities to remove those dependencies and to industrialize the Flagship's technology prototypes. The resulting products are going to be commercialized by Europe's own quantum entrepreneurship, with support by public investment funds to grow a full quantum ecosystem. European infrastructures (both terrestrial and in space) will contribute to bootstrapping the quantum market by adopting those products and integrating them into the fabric of the future quantum web.

To realize this vision, the EU needs a tightly integrated ecosystem of successful investments in innovation, infrastructure, entrepreneurship and skills. The scope goes even beyond the current multi-annual financial framework, both in terms of timescale and synergy with the growing number of national quantum initiatives, as well as in terms of cooperation with like-minded countries beyond Europe's borders.
In this way, our driving role as the engine of the next quantum revolution at global level will impact our society not only in terms of making the benefits of quantum technologies broadly accessible to citizens, but also in terms of the economic advantage inherent in making Europe the quantum valley of the world.

The next step to reach these ambitions is to focus the EU efforts on a large initiative based on a new European quantum agenda over the next decade, based on the following action lines:

I. Leadership in quantum technologies

1. Consolidate the EU basic research effort – The study of open scientific questions, including long-term, open-ended, curiosity-driven research, is crucial to the long-term impact of quantum technologies – to develop more applications as well as to prepare the ground for future new ideas. For this, MS funding organizations will coordinate among themselves and with EU programs (ERC, Marie-Curie, Horizon Europe Cluster 4)

These points are addressed in Chapter 2.1, dedicated to basic quantum science

2. Strengthen the link between research and industrial development targets with concrete deliverables in all areas, integrating and monitoring all the industrial and R&D ongoing initiatives to:

a) Deliver a quantum advantage for societal problems (like drug discovery, new materials prediction, logistics in smart cities) through quantum computers and simulators that are fully programmable and accessible from anywhere in Europe;

b) Implement a pan-European entanglement-based quantum network, including quantum repeaters for device-independent secure quantum communication;

c) Deploy a pan-European network of quantum gravimeters (Earth- and space-based) for high-resolution Earth observation and predictive natural resources management;

d) Deploy optical quantum clocks in Galileo for high-precision navigation;

e) Deploy quantum magnetometers in walk-through medical scanners for high-precision early-stage cancer detection.

Thanks to the strong contribution from QuIC to the SRIA, and its coordination with the vision published in the Strategic Industry Roadmap (SIR), objectives and recommendations aligning the research to the industrial requirements derived from real use cases are present in most of the chapters in this document.

II. Leadership in the quantum ecosystem

3. Foster industrialization of quantum devices through the production of quantum chips, crucial to facilitate miniaturization of quantum devices and their integration with other (integrated) devices, including control electronics and connectivity; and to improve fabrication reliability for large-scale uptake and mass-market applications. Quantum chip innovators will be provided with access to

a) Dedicated clean rooms and foundries for prototyping and production;

b) Open testing facilities where those components can be examined and assessed.

The alignment with the Chips Act in Chapter 2.2, as well as the specific recommendations in Chapters 1.1, 1.2, 1.3 and 1.4 dedicated to the technological pillars, provide a clear strategy for achieving EU leadership in the quantum ecosystem.

4. Deepen the integration of the European quantum industry ecosystem – An intimate link between European quantum solution providers (mostly SMEs) and the commercial users of quantum tech (mostly large companies) will be developed, by leveraging the existing European Quantum Industry Consortium. This requires specific measures like de-risking via attractive co-financing (major fraction of cost) of proof-of-concept R&D undertakings between SMEs and large end-users.

The strategy and the recommendations to achieve this objective are present in most of the chapters, thanks to the strong contribution from QuIC, and the alignment with their SIR.

5. Support entrepreneurial building to bridge the innovation gap – To reach the Digital Decade goal of creating EU unicorns also in quantum technologies, Europe urgently needs to close the funding gap of startups / SMEs relative to other regions, via:

a) Strong participation from public funding agencies (EIB, EIF, EIC, national investment banks like Bpifrance) in equity stakes;

b) Coordination between existing funds and the EU quantum fund, with the ability to lead funding rounds, finance or offer EU guarantee to EU investment groups with the mandate to lead funding rounds of EU quantum companies ('Fund of funds');

c) Clear, lean, and even rules on Foreign Direct Investment Screening, protecting EU capabilities while making Europe an attractive destination for private investors.

Chapter 2.5, dedicated to both public and private funding, provides specific recommendations to improve the funding process in the EU, to allow scaling-up of our start-ups, to ensure they can become the future global leaders.

III. Leadership in key enablers

6. Secure access to essential enabling technologies for quantum industry development

a) In-depth mapping of critical components, assessing localization (inside/outside of the EU) and substitutability of critical components, to be prioritized for

b) Re-shoring: support to develop EU supply chains for prioritized technologies;

c) "Friend-shoring": Bilateral / multilateral agreements to secure access to critical components from like-minded regions of the world.

In Chapter 2.2 and 2.7 we address the key points to guarantee sufficient production capacity of both quantum-specific and enabling technologies in the EU, as well the reliable supply of critical components. Recommendations are given on how to strengthen collaborations to achieve these objectives, and how to deal with the issues associated with export control.

7. Further infrastructure development – The first step to bring quantum products "made in Europe" into fruition will build on European quantum infrastructures such as EuroQCS (under EuroHPC), EuroQCI and the Space infrastructure for sensing, e.g. quantum gravimetry, and metrology, e.g. quantum clock navigation, in addition to secure quantum communications. This will require

a) Strengthening links among infrastructures and with the Chips for Europe initiative;

b) Boosting market for EU quantum manufacturing through adoption by procurement;

c) Creating competence centers giving access to training, capital and infrastructures;

Recommendations to implement these objectives are given within Chapters 1.1 to 1.4 dedicated to the technological pillars, as well as in Chapters 2.2 and 2.7 dedicated to engineering & enabling technologies and International collaborations

8. Attract talent and develop skills – To meet the foreseeable demand for talent, prevent a skills gap, and grow an ecosystem of well-informed business leaders, high-performing QT developers and educated end users, the EU needs to act within competence centers, for developing

a) Upskilling programs for industry workforce;

b) Academic programs for new audiences like engineers, computer scientists, chemists;

c) Programs to inform the decision makers in industries like telecommunications, chemistry, pharmaceuticals, finance, cybersecurity, and logistics.

Chapter 2.3, Education & Workforce Development, provides recommendations for immediate actions, to reduce the risk of shortage of qualified professionals, which could potentially undermine Europe's competitiveness and technological sovereignty in quantum technologies.

This will also require better exploitation of available resources, by promoting Equality, Diversity and Inclusion, by widening the quantum community in the broadest possible sense. A Strategy for Europe, and recommendations for immediate actions, are given in Chapter 2.8, Social and ethical values.

9. Take a global lead in standardization of quantum technologies – This will accelerate market uptake by providing reliability, consistency, and interoperability with existing infrastructure, systems, and components.

a) The work will be organised by CEN/CENELEC, so that European interest are guarded, to avoid fragmentation and focus on Europe's position in a global market.

b) This requires discussion and proposals at the European level, as well as global coordination with ISO, ITU, ETSI and other relevant standards-developing initiatives.

Chapter 2.4, Standardisation and benchmarking, gives directions and makes recommendations to ensure Europe takes a proactive approach in the development of standards and benchmarks, in coordination with other EU initiatives like EuroHPC-QCS and EuroQCI.

IV. Coordination and governance

10. Create synergies with Member States – Key to establishing Europe's quantum leadership is coordination with national quantum initiatives and funding organizations for

a) Future sustainability of upcoming quantum infrastructures, e.g. via new instruments such as European Digital Infrastructure Consortia for all areas;

b) In support of entrepreneurship via dedicated funding/investment instruments;

c) By actively addressing widening countries to realize the EU's full QT potential.

d) By establishing a structure bringing together all MS with the Commission for coordinating their funding programs, for discussing international cooperation matters, and for facilitating the creation of future partnerships such as EDICs.

Chapter 2.5, dedicated to private and public funding, together with Chapter 2.7, focused on International Collaboration & Export Control Regulation, provide specific actions to tackle this issues.

11. Partner with like-minded regions of the world – A policy dialogue about international cooperation in quantum will be initiated, to fix existing issues and to drive into common projects, delivering results for society at the EU and international level:

a) Developing early-stage quantum standards and regulations (including on post-quantum cryptography), providing a competitive advantage over competing actors;

b) Tackling current and potential future challenges about international trade, export control and IPR management, for the nascent quantum industry;

c) Setting up the framework for a successful international cooperation scheme on quantum-related topics for research and innovation starting from low TRL, based on a solid mutual understanding and shared, reciprocated values;

d) Working towards the establishing of a common quantum-benchmarking suite capable of pushing the best and most efficient quantum technologies through comprehensive, clear-cut and broadly accepted criteria addressing not only hardware characteristics, but also application focus and/or use-case relevance.

Recommendations for these points are provided in Chapters 2.6, with a strategy for Europe in Intellectual Property Rights, together with Chapter 2.4, to ensure the assets are effectively implemented in future standards and benchmarking.

12. Drive this agenda for Europe's quantum strategy across all EU programmes under the guidance of a new top-level Board, chaired by the Commissioner, with the mandate to define Europe's goals, and monitor their achievement, to realize the mission to make Europe the quantum valley of the world.

The Governance Structure, and how to make it evolve to adapt to the new EU quantum landscape, involving a multitude of stakeholders, spanning academia, industry, governmental agencies, state entities, is addressed in Chapter 2.10.

Part 1

Pillars of Quantum Technologies

1.1

Quantum Computing

1.1.A: Impact, societal challenges and quantum opportunities

The quantum computing pillar focuses on general-purpose Quantum Computers (QC) where quantum information is processed digitally, via logical gates, in a manner similar to today's general-purpose classical computers, or via measurements on large entangled states. The pillar regroups many layers of technology, from the individual modalities of quantum information processing to the algorithms and ultimate applications of these machines for a variety of use cases. The main objective is to develop quantum computing devices that outperform or accelerate existing classical computers, to solve specific problems relevant for industry, science and technologies, that could benefit from the execution of quantum algorithms. This "quantum advantage" can take many forms: it can mean solving useful industrial or scientific problems faster, or with better accuracy, or using less energy, or with a lower overall operational cost, or with a combination of any of these elements.

The existing first generation of quantum computing devices work in the Noisy Intermediate Scale Quantum (NISQ) regime, with noisy qubits and without quantum error correction. It is part of the efforts of the coming years to find out whether, and in what sense, one can hope to achieve quantum advantages in the near-term with quantum computers without Quantum Error Correction (QEC) but, for example, with error mitigation.

In the long term, the goal is to develop fault-tolerant quantum computers (FTQC), also referred to as large-scale quantum computers, as well as interconnecting these computers and trading quantum information between them, in effect building on both quantum computing and quantum communication capabilities to develop a 'quantum internet'.

The promise of a large estimated potential economic and societal value to industry and society over the coming decades, and the realization that already over one hundred known quantum computing algorithms could offer super-polynomial performance improvement over classic solutions, has driven the development of quantum computers. From a large collection of available use cases, below are presented few examples to represent industries that could benefit from the development of quantum computers.

Use case	Description
Optimization	Optimization problems are present in every industry. Anything that can be quantified with an objective function (often monetary cost or energy requirements) can be treated as an optimization problem. Examples of optimization problems are the routing of vehicles, the best distribution of resources among machines in a factory or improving pulse shapes in magnetic resonance imaging for enhancements in cancer detection. Optimized processes can have tremendous advantages for society as they commonly have fewer emissions and less waste.

Nitrogen fixation	Nitrogen Fixation is an essential technique to produce fertilizers used in agriculture to increase crop yield. This process involves converting molecular nitrogen (N2) in the air into ammonia (NH3). It is an essential reaction for life as biosynthesis of all nitrogen-containing organic compounds such as amino acids or proteins. In that sense, some industrial processes, like Haber-Bosch, reproduce this reaction outside a biological environment. But these processes are costly in energy, using over 1% of the world's total produced energy. In addition, they create a considerable number of residues that are not good for the sustainability of nature. Because of this, it is crucial to tackle this problem to find a way to replicate these processes more efficiently. Discovering new processes requires the accurate calculation of binding energies in order to understand reaction pathways. Exact calculations are even for medium size molecules forbiddingly hard for classical computers, as memory requirements scale exponentially in the size of the problem, unlike quantum computers, which are hence an indispensable tool in the development of such chemical processes.
Machine learning	Machine learning (ML) is an essential tool ubiquitous in various industrial processes and intelligent solution finding, ranging from image recognition to smart prediction algorithms for product recommendation. Most ML models rely on neural networks as their central building block, optimizing network weights for the model and task. Quantum computers offer the potential to fundamentally accelerate specific computational tasks, particularly in cases where the core of a problem consists of manipulating large sparse matrices, such as those occurring in ML. Here, it remains to be explored how quantum computing can be applied to improve the performance neural network architectures via fully quantum or classical-quantum hybrid algorithms.
Cryptoanalysis	An FTQC will be capable of running Shor's algorithm, which can find the prime factors of any integer in polynomial time. This capability threatens most existing protocols whose security relies on large prime numbers, such as RSA, but also protocols relying on elliptic curves, such as Diffie – Hellman. This perspective highlights the need to develop quantum communication networks, which will be discussed in this document, but also to find classical "post-quantum" encryption algorithms.
Drug discovery	Discovering new potent drug molecules usually requires understanding in which mode and how strongly a drug candidate binds to specific molecules in the human body, and how biomolecules fold. These molecular dynamics calculations are enormously costly on classical computers but can be sped up significantly in quantum computers.
Battery development	Energy storage via batteries has become central in our technology-based society. As we increasingly rely upon renewable energy sources such as wind, wave, and solar, our need for efficient energy storage technologies increases. Quantum computers will be valuable for developing battery technologies with optimum design qualities (performance, energy density, cost, lifetime, and recyclability).

1.1.B: Scientific,technological and industrial challenges

1.1.B.1 Quantum computation stack levels

The QC system stack is based on the integration of the quantum processing units (QPUs) along with the required infrastructure for housing, shielding and signal routing, as well as the control electronics, firmware, and the software stack, as shown in Figure 1.1.1.

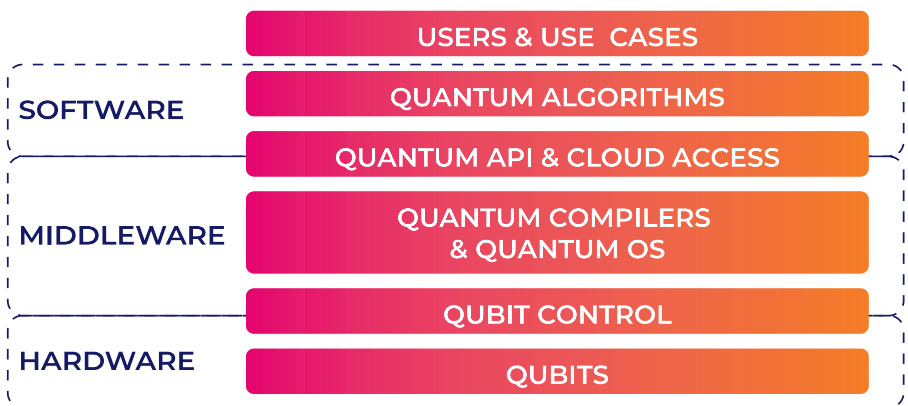

Figure 1.1.1: Schematic of a quantum computing stack

General-purpose quantum computers based on QEC will require the integration of millions of qubits that can be operated with high fidelity. The development of large-scale quantum computers requires efforts on all layers of the quantum-computing stack. This requires the development of:

- Quantum materials that can provide a highly reproducible and excellent environment.
- Qubit layers based on fabrication methods that are innovative, high-yield, and of high quality.
- Cryogenic environments and cryo-compatible electronics when necessary.
- Hetero-integration across several platforms and 3D design for scalability.
- Quantum control methods that allow for high-fidelity operation as well as automated tuning and autonomous operation.
- Control electronics, integrated optics and interconnection of qubits that are scalable. Key challenges to address are power consumption, heat dissipation, size, and scalable control such as multiplexing and shared control.
- Strong synergy between software and hardware, allowing for mid-circuit measurements, active feedback, error correction, as well as capabilities for high-level programming of quantum algorithms.
- Hybridisation with high-performance computing (HPC), to run quantum computers as quantum accelerators for supercomputers.

These challenges will need to be overcome to develop a roadmap towards FTQC based on an increasing quality and quantity of qubits. These technological challenges furthermore require an increasingly active role of the European industry. Moreover, strong collaboration between research and industry to create fast and effective feedback loops as well as co-design of the entire computing stack is essential to take full advantage of the power of FTQC.

NISQ devices

Currently, the field of quantum computing is still in its infancy. Today's QCs have quantum chips with a limited number of noisy qubits, due to interactions with their environment. This noise results in a larger probability of error at each junction of the calculation chain, and higher rate of error in the results. These devices are thus termed NISQ.

The currently available NISQ devices, which are physical implementations of a gate model QC, are constructed from a limited number of noisy qubits (i.e., not error-corrected) with limited connectivity, and therefore can only perform a limited number of imperfect operations in their limited coherence time. Nevertheless, NISQ devices can be used for special purpose applications, through shallow algorithms, or by incorporating the noise. Another way to build useful NISQ devices is to tailor them to a specific application, by co-designing hardware and software together, potentially lowering the requirements on the number and/or quality of qubits which are needed to solve a particular problem, similar to ASICs (application-specific integrated circuits) in classical computing.

It is unclear what impact NISQ computing will have on industrially relevant problems, because such algorithms involve a large number of qubits and thousands of consecutive gate operations, in order to compute expectation values to an accuracy that is competitive with high-performance classical supercomputers.

As a rule of thumb, any device with fewer than 50 logical qubits is unlikely to provide some form of quantum advantage, since it can be emulated with a classical computer. However, NISQ computers with more than 50 qubits may emulate physical systems that are far beyond the reach of conventional computers because of the exponential memory resources of quantum registers. Proof-of-concept demonstrations have been performed, enabled by advanced post-processing and error-mitigation techniques (not to be confused with error-correction) that can handle large data sets. NISQ is therefore a driver of development within device technology, control systems, and quantum software, which is necessary to advance the technology toward the precision and scale required for FTQC.

Fault-tolerant quantum computing

The only algorithms providing a proven exponential speedup require an error rate that is decades away at the rate of improvement we are currently witnessing. The only way to accelerate the race to very low error rates is to group several imperfect physical qubits into a better "logical" qubit. The idea is to redundantly encode information, and use this redundancy to detect and correct errors.
While this idea makes it possible to reach the very low error rates we need, it introduces a significant overhead in the number of qubits, and strong design constraints for the chip:
- It is estimated that up to thousands of physical qubits (with certain types of errors and state-of-the-art fidelities) will be needed to make one logical qubit, which can then be used for FTQC;
-The largest real quantum computers currently feature a few hundred physical qubits that are not good enough to run effective error correction;
-It is expected that achieving quantum advantage will require hundreds to thousands of (logical) qubits with a very low error rate;
It follows that inventing new solutions (qubit designs, chip architectures, error correction codes...) with lower hardware requirements, and using scalable technologies, is a major challenge for both the basic research and the industry.

1.1.B.2 Qubits

The lowest part of the stack contains the main hardware modalities considered for the construction of QC. At the moment different solutions are being explored, and it is not clear which one will be the finally adopted technology. It is in fact conceivable that some platforms will be able to operate efficiently up to the NISQ regime or will be optimized for special-purpose quantum computers, such as quantum annealing (QA) and quantum simulation (QS), that will be discussed in the quantum simulation chapter, while other platforms may provide access to large-scale integration, enabling the implementation of FTQC. Examples of the most promising quantum hardware platforms are discussed in the following sections.

Superconducting qubits

Superconducting qubits are one of the most mature technologies for quantum computing. They consist of artificial, macroscopic quantum devices offering great engineering flexibility. Their coherence time has improved over five orders of magnitude since their inception. The main challenge is to keep that momentum going in the face of challenges of their sensitivity to ionizing radiation and relatively large physical footprint.

Superconducting qubits are based on electronic circuits made from superconducting materials, patterned on a substrate, featuring a non-linear element, usually a Josephson junction, used to engineer the energy levels of the circuit.

The most common superconducting qubit is the transmon, in which the different energy levels correspond to a specific integer number of Cooper pairs on a superconducting island. Transmons have become the industry standard because of their resilience to external noise compared to previous technologies, such as flux qubits and phase qubits. They are used in today's largest quantum computer (in terms of number of qubits), and feature lifetimes of hundreds of microseconds.

More recently, two main new approaches have emerged, promising even longer lifetimes and better gate fidelity. The first approach is to develop circuits more strongly isolated from the environment than transmons, able to withhold quantum information for a longer period of time. This includes fluxonium qubits (which have demonstrated lifetimes of a few milliseconds) or zero-pi qubits. The second approach (bosonic codes) is to use the circuit to stabilize quantum states in a resonator (e.g., electromagnetic or acoustic waves resonators) and actively correct some errors. This includes cat qubits or GKP (Gottesman Kitaev Preskill) qubits. Bosonic codes promise a shortcut towards FTQC by significantly reducing hardware requirements.

With superconducting circuits, one can take advantage of their flexibility in engineering their quantum properties and interfaces to develop various NISQ architectures. Many NISQ computers will be forward-compatible with FTQC though, and there is not really a need to distinguish between the hardware for the two.

Superconducting qubits have been integrated to large systems of up to more than 120 qubits that have passed a “beyond classical” benchmark, as well as to much larger systems beyond 400 qubits that are currently being tested. Superconducting qubits have also demonstrated the main ingredients of quantum error correction including first logical qubit operations. Single-qubit gates, two-qubit gates, and qubit readout have all been demonstrated, at the performance threshold for quantum error correction. A challenge remains to demonstrate large integrated systems with this control all the time, in order to perform NISQ and FTQC.

Objectives and recommendations, short term (2024-2026)

- Push the technology towards the basic demonstration of NISQ computing and QEC for FTQC.
- Focus on material technologies and processing techniques to produce better and more reliable components.
- Design computational gates with lower errors, an important prerequisite for scaling up quantum computing.

Objectives and recommendations, medium term (2027-2030)

- Superconducting quantum circuits are made of different materials and require different processing expertise than circuits perfected in the semiconductor industry. There is therefore a great need for technology transfer and focused development of superconductor technology in larger manufacturing facilities. Moving from university cleanrooms to reliable manufacturing facilities for large-scale QPUs will be quite costly but is important to achieve technological sovereignty and secure critical supply chains.
- With the design and validation of QC processors and systems at the presently available level (up to about 100 qubits), it is important to push the technology toward the basic demonstration of NISQ computing and QEC for FTQC. Scalable characterization techniques and system-engineering bottlenecks should be identified at this level.
- At the same time, basic device technology must continue to search for ever-better concepts enabling lower-error computational gates, a key requirement for scaling up quantum computing.
- Device integration, electronics packaging, and signal delivery are other important engineering tasks.
- There is a need for development of control systems based on electronics conventionally placed at room temperature as well as at cryogenic temperatures electronics.
- Fabrication facilities to prototype and test solutions towards error-corrected universal QC: higher gate fidelities, more qubits.

Semiconductor-based qubits

In charge semiconductor qubits, quantum information is encoded in the electronic spin. Several different implementations have been explored so far, with the spins being bound to dopant impurities, or bound to charges confined in quantum dots through electrostatic gating, in combination with physical or band-structure confinement. The qubit states can then be encoded on single or multiple quantum dots. Spin manipulation can be achieved via direct interaction with a magnetic field, via a current line or using micro-magnets, or via interaction with an electric field, using the spin-orbit coupling present for instance in holes. Universal quantum logic is realised via electrical signals that coherently control the spin state and the exchange interaction between neighbouring electron (or holes) spins. Semiconductor qubits can be coupled through short, mid, and long-range quantum links, thereby offering a highly flexible platform with the potential to accommodate for the most promising QEC schemes. Mid-range and long-range coupling, realized today using resonators, offer great architectural flexibility, allowing individual qubits clusters or QPU of small/medium size to be coupled together, for large-scale quantum computing.

In terms of device structure, semiconductor qubits have important commonalities with conventional transistors. Most importantly, they can be fabricated using the advanced tools and technologies of the semiconductor industry, which can eventually open a viable path to their large-scale integration.

Compared with the currently most advanced qubit platforms, semiconductor qubits have been studied for a relatively short amount of time. However, this technology may ultimately offer strong scalability, and significant progress has been made in recent years, particularly using silicon- and more recently germanium-based structures, to achieve high-fidelity one- and two-qubit gates.

Taking advantage of the great technological background of the semiconductor industry, semiconductor-based qubits will also benefit from the most advanced technological breakthrough, and then semiconductor-based QPUs can be envisaged as a 3D or monolithic assembly of the quantum core with its control cryo-electronics.

Objectives and recommendations (2024-2026):

- Focus on the high-fidelity operation of small-size quantum processors with an extensible architecture to outline a scalable roadmap to large-scale quantum computing.
- Build up European infrastructure, know-how and a supply line for the fabrication of qubit chips using advanced semiconductor manufacturing techniques.
- Prefer device realizations offering low disorder and high-yield and reproducibility.
- Focus on implementation offering the true possibility to reach high connectivity and explore advantages of shuffling techniques of qubit registers.
- Investigate opportunities in distributed quantum computing where individual qubit modules are interconnected by on-chip quantum links that offer high connectivity.
- Investigate the scale-up of cryogenic systems, to overcome technological bottlenecks, such as heat load demands and power consumption.

Objectives and recommendations (2027-2030):

- Mature technology and focus on increasing qubit quality, quantity and interconnectivity.
- Integrate quantum and classical hardware (through cryogenic electronics and/or efficient wiring and control) to develop quantum processors that can be scaled to very large numbers (eventually millions) of qubits.
- Target the realization of a semiconductor-based, full-stack computer with a quantum core containing hundreds to thousands of qubits, and develop a roadmap toward fault-tolerant quantum computing

Trapped ions

Trapped ion qubits are based on atomic ions (e.g., Be+, Ca+, Sr+, Ba+, Yb+) confined in traps. High fidelity and long coherence times are the key performance aspects of this technology. Traditionally, ion traps have been operated at room temperature. Nowadays, systems based on microfabricated ion trap chips are often operated at cryogenic temperatures in order to reach a better vacuum and suppress electric noise from the trap. Qubits are encoded in the internal states of the ions. There are three main strategies for encoding a qubit:

- Two electronic states, typically the ground state and a metastable excited state, with an energy separation in the optical spectrum (hundreds of THz).
- Two hyperfine levels with an energy difference in the GHz range.
- Two Zeeman sub-levels of the ground state, with an energy difference in the MHz range.

Ions form self-arranged crystals so that particles can be individually addressed. Gates are implemented by exploiting the common modes of excitation of a crystal, which can be excited by laser light to exerting state-dependent forces. Since the interactions are mediated by vibrational modes of the crystal, the interactions are not limited to next neighbour; instead of any ion in the crystal can be made entangled to any other one with high fidelity. The qubit control with lasers allows a faster operation than with microwaves, but the control with microwaves offers decisive advantages in scaling up to a larger number of qubits, compared to control with laser light. Based on the outstanding shielding of ions from their environment, and high level of control, trapped ions have achieved fault-tolerant levels of control, realized coherence times of more than 1 hour, and are leading across platforms for various benchmarks.

The main weakness is that scaling the number of particles to large numbers is complicated. The targeted size of the quantum chip is relatively large, and it is not so clear how these chips will scale to a thousand or a million qubits. Currently QC hardware based on trapped ions control up to about 100 qubits, both in a one-dimensional crystal, or distributed in several trapping zones, with early implementations of two-dimensional control. Commercial quantum computers with hardware of a few tens of ions are already present in the market. Research towards more complex and scalable trap architectures is ongoing.

One of the most promising short-term applications of QC is the Variational Quantum Eigensolver (VQE) an algorithm to solve quantum optimisation problems following a hybrid classical-quantum approach. Recently, a VQE proof of concept was implemented for a trapped-ion quantum computer, used to minimise the quantum resources required to estimate the ground-state energy of the water molecule (H2O) using 11 qubits and 143 entangling gates.

Objectives and recommendations, short term (2024-2026)

The development of trapped ion quantum computers must find scalable solutions. These may include:

- Devising new traps for realizing 2D crystals at low temperature,
- Devising new modular structures for coherently coupling separate one-dimensional chains,
- Optimizing methods for shuttling the ions in chip traps, developing integrated photonics to scale laser beam delivery.
- Simultaneously, error rates and times for initialisation, readout, and manipulation, as well as gate speeds, should be further lowered. One way of improving gate quality is to operate traps at temperatures of 4 K, even though gate fidelities exceeding 99% can be achieved with room-temperature traps.
- It will also be necessary to prepare for interconnection between quantum processors. Ions that are levitated in an evacuated chamber can be easily moved: this suggests a potential approach for interconnection. Extending the scope beyond ion transport (between processing zones on the same ion-trap chip as well as ion transport between different ion-trap chips), photonic coupling of sub processors should be further investigated.
- In parallel, better integration of optical, photonic, and electronic components with the ion trap in a way supporting scalability (both in the number of ions, as well as repeatable industrial production) should be explored. Integrated cryo-compatible solutions for signal multiplexing will have to be devised.
- In the next few years, first error-correction implementations with large numbers of qubits are expected. Reliable integration with HPC resources should be validated.

Objectives and recommendations, medium term (2027-2030)

- The medium and long-term perspective includes realising a fully integrated scalable quantum device, encompassing interconnected (or segmented) traps, control electronics, and optics, in a reliable, industrially feasible, and scalable manufacturing process. Such devices should be able to support a few thousand qubits, with control of ions beyond one-dimensional arrays, with the promise of scalability to tens of thousands of qubits.
- The software-stack needs to be extended beyond gates, and include ‘interfacing’ interactions, including transport operations as well as potential interfaces between separated trap structures (both locally and remote).

Neutral Atoms

Neutral-atom qubits are based on trapped Rydberg atoms. Ultracold neutral atoms, trapped in programmable arrays of optical tweezers and/or in optical lattices, provide quantum registers with controllable connectivity. Quantum information is encoded in either spin or electronic degrees of freedom.

Single-qubit gates are realized with microwave and laser control pulses, and two-qubit entangling gates are realized via excitation to high-lying Rydberg states.

This platform not only enables analog and digital quantum computations, but also has the potential of offering the largest scalability (exceeding thousands of qubits) and longest coherence times, also thanks to techniques developed in the context of quantum optics and frequency metrology. Moreover, as in the case of ion-based qubits, neutral atoms qubit can be operated at room temperature. On the other hand, the repetition rate of this platform is currently lower than other platforms, mainly limited by the time required for the preparation of the qubit array and a destructive readout. As of today, quantum registers of approximately 100 qubits and two-qubit gate fidelities >99% have been demonstrated. These figures are rapidly increasing over time and no fundamental limits to scalability and fidelities have been identified so far.

The interfacing with classical electronic hardware is more complex compared with other technologies like solid state qubits, and it requires complex state-of-the-art optical setups, also in need of integration schemes for scalability.

Objectives and recommendations, short term (2024-2026)

- Reduce the time needed for the preparation of the qubit arrays by developing improved techniques for deterministic loading of individual atoms in the optical tweezers arrays and/or developing novel techniques for the reordering of partially loaded arrays.
- Develop enhanced techniques for faster, high-fidelity imaging and novel non-destructive readout techniques to further improve the repetition rate.
- Improve the capability of local addressing to manipulate individual qubits and qubit pairs.
- Design robust and reliable optical, optoelectronic, and electronic components that can be better integrated in neutral-atom-based machine to grant the highest possible uptime and reduce the need of maintenance.

Objectives and recommendations, medium term (2027-2030)

- Develop reliable cryogenic setups that will greatly improve the lifetime of atoms in tweezer, which will allow to increase the number of qubits, and reduce the blackbody radiation, that will extend the lifetime of Rydberg states with a consequent increase of fidelity of two-qubit gates.
- Improve the quality of Rydberg excitations by new excitation schemes and better laser sources by exploring new excitation schemes and developing more powerful and reliable laser sources in the UV spectral range.
- Develop new solutions for fully fibered or integrated photonic optical setups, also working in the UV region, to allow the engineering of more compact, modular and fully integrated setups and further improve the system reliability and uptime.

Photons

Photonic qubits are based on single photons (discrete variable approach) or on special squeezed states of light (continuous variable approach). They feature very low decoherence time, a strong asset for quantum computing. Another distinct feature is the mobility of photonic qubits, allowing to implement long-range gates and additional generation of qubits during the computation. Photonic qubits also have excellent prospects for scalability since they are compatible with photonic integrated circuits (PICs). While established PIC materials, like those based on silicon nitride, can built on existing manufacturing capabilities, the upcoming lithium niobate on insulator (LNOI) platform allows for efficient squeezed state generation and fast switching.

Although two-qubit photon gates are not deterministic in the discrete-variable approach, two squeezed states can be deterministically entangled in the continuous-variable approach. Breakthrough photonic quantum computing schemes have been proposed, like Gaussian boson sampling, or measurement-based quantum computing (MBQC), to reduce the overhead of components to build a logical qubit and open a path towards FTQC.

In MBQC, quantum algorithms are implemented by performing single qubit measurements with a basis contingent on previous measurement results. Qubits are continually produced, entangled, and measured. At the physical level, the photonic quantum computing architectures are based only on linear optics components such as sources, multiplexers/demultiplexers, switches, phase shifters and detectors, without the need for quantum memories.

Finally, while the quantum processor itself can be operated at room temperature, the lowest temperature required for some components (e.g., the superconducting nanowire single photon detectors) remains above 1K, thus limiting the cryogenic requirements and power consumption.

In the discrete variable framework, a first challenge is associated to the qubit sources, which must feature simultaneously high brightness, high single photon purity, and high photon indistinguishability. In the continuous variable framework, the main goal is to build cluster states with a large number (hundreds) of entangled squeezed light states.

On the detection side, high-performance single photon detectors with near-unity efficiency, low noise, low timing jitter and low latency, for high-speed operation compatible with feed-forward are needed. Superconducting nanowire single photon detectors are the technology of choice for this purpose. Beyond the single detector stringent performances, architectures able to resolve the number of photons to enhance the quantum computing fidelity and reduce errors are highly desirable.

Regarding the processing of photonic qubits, one critical challenge is to develop a set of passive integrated components with near zero insertion losses, to allow for high quantum computing depth, as well as to develop low-loss, fast switches for the implementation of active feed-forward required for MBQC, and compatible with the operation of cryogenic detectors to achieve seamless integration of both types of components.

The roadmap of photonic quantum computing starts with the demonstration of NISQ quantum processors with a few qubits. The next goal will be to build fault-tolerant quantum computers with tens of qubits. The long-term objective is to build universal fault-tolerant quantum computers with a very large number of qubits (hundreds of thousands of physical qubits). Ultimately, a major boost to photonic quantum computing would be given by realizing high-efficiency quantum-logic gates between two optical photonic qubits. Various routes are possible, typically based on atoms or quantum dots inside high finesse optical cavities. Very promising results have been obtained recently by using Rydberg 'superatoms' inside a cavity, reaching the desired regime of an optical π phase shift at the single photon level. Though these experiments are still at the proof-of-principle stage, they certainly indicate a promising direction, where the very high efficiency of one-qubit gates for photons might be combined with high efficiency deterministic two-qubit gates.

Objectives and recommendations, short term (2024-2026)

- Development of single photon and squeezed light sources with high efficiency, high purity, and high indistinguishability. Increase the performance of deterministic single-photon sources from the current efficiency of 50% to > 70% (increase in generation speed in one optical mode). Increase single-photon purity (indistinguishability) from 95% to 98%.
- Efficient generation with increased fidelity of cluster states of entangled photons (temporally and/or spatially encoded).
- Development of integrated circuits with near-zero propagation losses and coupling losses, embedding several thousands of passive components. Assemble optical QC platforms of up to 50 digital qubits, in fully reconfigurable Integrated Circuit (IC) platforms
- Develop ICs and sources at mutually compatible wavelengths, including telecommunications (C-band) and 935 nm (practical for solid-state sources).
- Develop high-fidelity two-qubit gates, in particular deterministic two-qubit gates between optical photonic qubits.
- Development of single photon detectors with near-unity efficiency and high operating speed compatible with the implementation of feed forward. Integrate Single Photon Detectors (SPDs) on ICs.
- Assembly and demonstration of quantum computer hardware with record number of qubits (tens of qubits) or qumodes (hundreds of modes). Deliver reconfigurable optical circuits of up to 200 modes for use in specialised algorithms.

- Develop a framework of compilers, assemblers, and libraries for controlling the platform and hardware stack via a user interface.

Objectives and recommendations, medium term (2027-2030)

- Further improve the performance of deterministic single-photon sources, to > 80% efficiency (increase in the generation rate in an optical mode) and single-photon purity (indistinguishability) close to 100%.
- Development of fast integrated switches with near zero propagation losses compatible with feed forward.
- Development of single photon detectors with near-unity efficiency with high operating speed compatible with the implementation of feed forward and the ability to resolve the number of photons.
- Photonic quantum processors with active feed forward, from modular to highly integrated platform. Increase the number of qubits in optical QC platforms to 1000.
- Improve the semiconductor technology (reproducibility and large-scale production of single-photon semiconductor emitters) so that several dozen identical emitters can be fabricated.
- Have multiple identical single-photon emitters and routers to distribute up to 1000 single photons in ICs with hundreds of modes each. Fully integrate sources, circuits, and detectors on-chip.
- Deploy error correction on a small number of logical qubits.

Color-center qubits

Color-center qubits consist of a variety of optically active defects in wide-bandgap semiconductors. The currently most advanced example in terms of number of qubits, control fidelities and protocols demonstrated is the nitrogen-vacancy (NV) center in diamond. Various other color-center qubits with potential advantages over the NV center are now being intensively investigated as next generation platforms. These qubits include the silicon-vacancy (SiV) and tin-vacancy (SnV) in diamond, the divacancy (VV), the silicon-vacancy (VSi) in silicon carbide, and the T-center in silicon. While these qubits all share similar properties with a strong synergy in the physics and quantum control, each brings unique advantages and opportunities.
Some of the key properties of color-center qubits are:

A ground-state electron spin that provides a high-quality qubit, typically controlled by microwaves pulses (gate fidelities >99.9% and coherence times > 1 second, demonstrated).

The electron-spin qubit can be initialized and measured using lasers, and spin-photon entanglement makes it possible to connect color-center together through photon interfaces.

Each color center provides additional qubits in the form of nuclear spins (either in the host material, or native to the center), making each center a natural multi-qubit system.

The solid-state host materials provide potential scaling through integrated optics and electronics.

Depending on the color-center qubit, high operation temperatures are possible, with for example the NV center keeping excellent spin coherence all the way up to room temperature.

The state of the art for color-center qubit is that many of the basic building blocks for quantum processors have been demonstrated. Examples include high-fidelity single and two-qubit gates (>99.9%), processors with up to 10 qubits, the fault-tolerant operation of a logical qubit of an error correction code, and optical entanglement interconnects (including over long distances).

Two main paths for scaling towards larger systems can be identified. The first is to connect many small (2-10 qubit) system modules together through optical interconnects. This approach derives its scalability from modularity (connecting independent modules) and is expected to require cryogenic temperatures (up to e.g. 20 Kelvin for qubits in SiC). A key advantage is that the optical interconnects enable flexible connection topologies, so that all types of QEC codes can be implemented, including for example low-density parity-check codes. The second approach is to use the direct spin-spin interaction between color-center qubits by creating arrays of qubits. As no optical interconnects are required, this approach can operate at high temperatures (e.g. up to room temperature for the NV center). Note that these approaches can also be combined.

For both approaches, the key challenge now is to demonstrate a path towards large scale systems (~1000 qubits and beyond). This requires a strong push in device integration, including integrated controls and electronics, integrated optics, and integrated efficient spin-photon interfaces. At the same time, qubit control fidelities need to be maintained and further improved.

Objectives and recommendations, short term (2024-2026)

- Focus on device fabrication and integration (integrated optics and qubit controls) will be essential for future scalability.
- Develop a blueprint/roadmap towards a 1000-qubit system with scalable fabrication methods beyond 1000 qubits.
- Demonstrate efficient entanglement optical interconnects using integrated devices (on-chip and/or between chips).
- Demonstrate the reproducible creation (e.g., by ion implantation) of coupled color-center qubit systems.
- Demonstrate small-scale quantum devices (20-100 qubits) with high-fidelity control (> 99%). Benchmark gate fidelities and quantum error correction operation.

Objectives and recommendations, medium term (2027-2030)

- Focus on scalable fabrication and control through device integration. Bring together integrated optics and control electronics. Focus on cost, size, and stability, in addition to high-fidelity control.
- Benchmark a fault tolerant quantum error correction. Show operation fidelities above threshold.
- Demonstrate and characterize the fabrication of chips/devices with up to 1000 qubits.
- Demonstrate operation of medium-scale quantum processors with 100-1000 qubits with high-fidelity control (>99%).

Hybrid quantum systems

The basic principle of hybrid quantum systems is to use two different quantum systems coupled in a single experimental setup. Examples of hybrid quantum systems include atoms, ions, dopants, or artificial atoms (e.g., quantum dots) coupled to photon cavities, or even atom-ion systems. The advantage of a composite system is that the interactions arising between the two quantum systems can be used as a new parameter to steer the quantum evolution and realize gates or quantum non-demolition readout schemes. Hybrid systems provide a strong potential in the development of new QC architectures that use new methods for implementing gates through inter-system interactions, and that provide methods for increasing the size of QC (e.g., by coupling QCs through photonic links, or other means to generate a quantum network).

An advantage of hybrid quantum systems lies in their ability to incorporate a greater number of variables compared to homogeneous quantum systems. This expanded "quantum toolbox" can potentially lead to the development of new and advanced architectures for quantum computing. However, the main drawback is that generating hybrid quantum systems may require more complex setups and a higher degree of control over experimental parameters.

Several types of hybrid quantum systems have been realized in the last decades. Coupling of atomic or atomic-like degrees of freedom to photons in a cavity has already led to experimental demonstrations of quantum simulation, photon-mediated long-range interactions and entanglement, or quantum non-demolition measurements. Atom-ion hybrid systems have been brought to extremely low temperature, and coherent control of atom-ion interactions were demonstrated by using Feshbach resonances.

Objectives and recommendations, short term (2024-2026)

- Increase the coherence time of atoms/ions coupled with cavities.
- Develop new architectures that increase the number of atoms/ions coupled to cavities.
- Demonstrate coherent evolution in an atom-ion system with control of inelastic collisions.

Objectives and recommendations, medium term (2027-2030)

- Demonstrate first working QC architectures that make use of more than one quantum system.
- Coherently couple more than two quantum systems via photonic links

Other relevant technologies

Molecular spin-qubits are based on electron and nuclear spins in magnetic molecules, such as vanadyle compounds, antiferromagnetic rings, or the Buckminster-Fullerene C60 molecule, and carbon nanotubes.
Topological qubits are based on braiding anyons such as Majorana quasiparticles. Already about twenty years ago, it was predicted that zero-energy quasiparticles that appear at the edges or in the vortex cores of topological superconductors would effectively behave like Majorana quasiparticles. However, a conclusive observation of Majorana quasiparticles is yet to be achieved.

Ambitions common to all these different hardware modalities are:

- Enhance the NISQ processing regime with error mitigation methods, enabling deeper algorithms, forging progress towards fault-tolerant universal quantum computing.
- Increase the number, density and connectivity of qubits while demonstrating improved performance. Improve quality of qubits, including better coherence times and gate fidelities, targeting 99.9% for both one- and two-qubit gates on a scalable, multi-qubit quantum processor by 2027.
- Design and implement new architectures, including 3D setups and hybrid systems, together with new assembly techniques that can ensure a modular production of quantum hardware, thus favouring future large-scale production of QC devices.
- Make quantum computers reliable and usable in data centers with classical HPC, while ensuring their energy efficiency.
- Develop industry-standard fabrication facilities that can assemble and integrate large high-quality quantum processors.
- Demonstrate interconnection and information exchange between different quantum computers.
- Promote the growth of an expanded industry for demanding components and technologies used in QC (e.g., sources of atomic samples, precision lasers, vacuum technologies, cryogenic technologies, low-noise amplifiers, control electronics) with the aim of enhancing standardization and reducing production costs.

1.1.B.3 Qubit Control

Optimal operation of quantum computers requires the characterization, tuning, and control of qubits.

Qubit characterization involves measuring the properties of individual qubits and the coupling between pairs of qubits. Efficient (i.e., accurate and fast) characterization protocols are essential to ensure optimal and stable qubit operation. Periodic restauration of qubit performance is necessary to counteract commonly present drifts in the qubit properties, or even the loss of the qubit itself.

Qubit control is the initiation and manipulation of individual qubits, which needs to be optimized for maximal fidelity. Careful orchestration of qubit control signals and reiterated qubit calibration routines are required to enhance the computational power of quantum processors. The fine-tuning of control signals should optimize the quantum hardware properties, which includes (if possible) to work at the lowest level of decoherence the system allows. It should also be fast enough to avoid fixed decoherence, avoid unitary errors from miscalibration or spurious degrees of freedom, and offer a rich gate set. Additionally, it should also provide quantum hardware developers with diagnostic information.

The energy consumption, the physical footprint, and robustness should be gradually improved. This can be achieved, for example, by placing parts of the control system in proximity to the QPU in their cryogenic and/or Ultra High Vacuum (UHV) environment.

To estimate the efficiency of a quantum computation, different elements must be considered. The operation count of the quantum algorithm, the encoding of the problem, and the cost of measuring the outcome of the calculation.

On top of physical qubit control, we must be able to integrate, in an efficient way, standard computing parts, as well as quantum computing parts. This will allow for best computing speed, enabled by optimal workflow management. It will also shorten the time for reconfiguration of the quantum circuits. This layer should lie ideally on the qubit control and the Operating System (OS) stack.

Implementation of fault-tolerant quantum computing

Reaching large scale quantum computing will be required to allow FTQC. Indeed, QEC requires a stringent increase in the number of physical qubits, to obtain logical qubits whose error rate is negligible with respect to quantum computing duration. Depending on the quality of the qubits obtained, this could lead to QPUs consisting of millions of qubits, for a very direct, problem-independent, and universal access to practical quantum advantage.

Reaching large scale quantum computing impacts all constituents of quantum systems:

The qubits themselves must be replicable and have limited variability in control signal specifications to enable their mutualization. Particular attention must be paid to optimizing signal mutualization in accordance with QEC schemes that can exhibit regular computing patterns.

The control electronics has to be integrated as close as possible to the qubits. This requires the ability to design cryogenic integrated electronics. Therefore, work has to be carried out to create design kits for existing CMOS technology nodes under cryogenic conditions, especially for semiconductor-on-insulator techniques that shows promising functional properties. This will require EU investment in DC/RF characterization capabilities under cryogenic conditions.

The readout amplification electronics used for today's QCs must be further integrated to be scalable. This requires an advanced superconducting device foundry to fabricate travelling wave parametric amplifiers (TWPA) on a large scale. Another challenge is to place the TWPAs closer to the qubits because they are sensitive to the magnetic field required to implement some qubit families, such as spin qubits. Another challenge is to increase the bandwidth of these amplification devices to increase the number of qubits readout they can amplify and limit their overall footprint.

The use of cryoelectronic near the qubits should not increase their noise levels. Therefore, 3D integration techniques for QCs must focus on identifying novel solutions to ensure high signal conductivity with low heat generation. Defining simulation tools for small-scale thermal management will be key to finding novel strategies without costly trial-and-error loops.

Communication between the cryostat and the room temperature electronics is not to be accomplished via RF wires, whose thermal conductivity and size would hinder their use at this scale. Alternative communication schemes, such as optical communication are being sought, but their integration capability must be guaranteed under cryogenic conditions.

The error correction schemes require decoding algorithms capable of finding the most likely error (decoding) in a small timeframe compared to the coherence time. Special efforts must be made to define efficient decoding algorithms and their hardware implementation to ensure that they provide good scaling characteristics in terms of error correction capacity, power, area and latency.

Efficient implementation of logical gate circuits over physical qubit topologies must be investigated. Promising solutions must be integrated into the compilation steps, to fully abstract the complexity caused by QEC and provide the user with an ideal programming environment. Such compilation steps require extensive optimization to reduce the overhead caused by abstraction. Therefore, the expertise from operational research in mapping and routing will be used in this perspective.

Overall, the complexity of FTQC systems is such that they require greater, transdisciplinary understanding, leading to move to actual system-level architectural design. Importing expertise from complex system design should help the quantum community find an optimized architecture that can be further explored for scaling. Defining system-modelling approaches based on best practice in modelling based system engineering and simulation are recommended, to overcome this complexity barrier.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Increase the number of qubits that can be simultaneously controlled in line with the development of quantum processors over the next three, six, and nine years.
- Increase the integration of these control devices (user interfaces, qubit interfaces).
- On the hardware side: increase the level of integration with the qubit's immediate environment; include qubit control elements in the semiconductor stack for serial manufacturing; optimise control signal management and make it scalable alongside the development of new, interconnected QPUs; improve the speed of operation, in particular to allow for fast feedback loops between qubit readout and control relevant for error correction; reduce noise injected from the control system side.
- Reduce lead times and costs by reducing the dependency on materials and components from non-European sources.
- Support standardisation of qubit control for future implementations.

1.1.B.4 Software stack, quantum operating systems, quantum algorithm compilers

The full software stack for quantum computers includes:

- The quantum firmware, enabling the autonomous, efficient, and error-robust manipulation of quantum computing hardware directly at the classical quantum interface. The term quantum firmware is currently conceptual in the context of quantum computers. Still, it will likely exist in some form, similar to how the firmware (lowest level of precise control software) works in classical computers.
- Quantum operating system, i.e., the software that manages the quantum hardware (qubits) and the classical hardware used to characterize and control the qubits. It oversees the execution of quantum algorithms at the machine level by optimizing hardware resources and provides users with an interface to enter instructions and receive output from the quantum computer. The quantum operating system must be able to control the hardware by controlling the operation of the different devices (e.g., lasers, voltages, electric currents, magnetic fields) and processing the data extracted from the detection of the quantum hardware.
- The compiler for analysing the quantum algorithms, and to map them most efficiently on the available QC hardware, thereby taking into account the qubit-qubit connectivity and topology, and, when available, QEC for detecting and fixing errors caused by decoherence and imperfect qubit manipulations. As with classic compilers, compilations will be executed as a series of passes, each representing a particular optimization and transformation step before translating the final stage into firmware control instructions. Such a compiler infrastructure will require a proper intermediate representation, ideally integrated with those of classic compilers to support hybrid codes.
- Software Development Kits (SDK) including debugging and testing/ verification facilities, lying on static analysis tools and formal verification.
- Programming languages for describing quantum algorithms at varying levels of abstraction.
- A runtime system, enabling dynamic compilation as well as dynamic instantiation of algorithm's templates.
- Multi-level scheduling solutions at the application, job, and QC execution level, to enable hybrid classic/QC algorithms, multi-tenancy operation, as well as efficient time- and space sharing when possible.
- High-level libraries and domain specific toolkits.
- Quantum Computing Platforms as a Service (QC-PaaS).

In addition, QC emulators running on digital supercomputers are essential for validating designs of physically feasible QPUs. Moreover, QC emulators are an irreplaceable tool for designing, analysing and benchmarking quantum algorithms.

As none of the currently available QC devices are powerful enough to run real-world problems, most of practical applications in QC are currently realized by using hybrid algorithms, combining classical with quantum computation. Practical applications often require the integration of quantum computing into existing HPC infrastructures in the form of hybrid classical and quantum computing resources. Calling quantum algorithms from classical computers requires developing interfaces between these two software stacks.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Develop quantum compilers with automatic scheduling capabilities, that incorporate calibration and quantum error correction coding/decoding routines in the main quantum algorithm.
- Develop resource estimation capabilities, to determine if a given device can or cannot run a specific piece of code.
- Demonstrate distributed programming capabilities on multiple hardware control back-ends.
- Standardize an intermediate representation framework that works across multiple technologies.
- Develop a hybrid classical/quantum software stack based on Application Programming Interface (API) and compiler directives, together with debugging/verification means.
- Develop machine learning-based operating systems that optimize the quantum hardware operation.

1.1.B.5 Quantum programming APIs & cloud, languages & access

i. Quantum programming APIs and cloud access and languages

Quantum Programming APIs and languages form the transition layer between users and quantum machines in the quantum computation stack. This layer is generally part of the general-purpose quantum SDKs (in the form of specific APIs or languages) that are used to implement quantum algorithms at the quantum gate level, as well as higher-level access options via domain specific languages or libraries (DSLs). Further, access should also be available at low-level, e.g., with direct pulse control for specific experiments. By providing the SDK with credentials for an API or a cloud platform, users can execute an algorithm they are designing on an actual quantum computer, or on an emulator running on high performance classical computers operated by the provider.

Future development opportunities lie in the modular integration of quantum computing into existing HPC infrastructures, in order to enable the execution of the important quantum-classical hybrid computing models. Such hybrid computing models are not limited to the well-known hybrid quantum-classical models such as the VQE for solving eigenvalue problems, e.g., in quantum chemistry and materials science, the Quantum Approximate Optimization Algorithm (QAOA) for solving optimization problems or the quantum Support Vector Machine (qSVM) for machine learning. In fact, any program code that contains a (small) part that can be (better) executed by a QC is a candidate for hybrid quantum-HPC.
Such hybrid approaches will have to be represented in the available programming APIs/ languages, likely in the form of hybrid toolkits.

ii. Remote access

Access to quantum systems will in many situations be remote and available, in some form, via the internet or a cloud-like setup. This alone is true since QC systems require classical systems as hosts for access and control.

One option (especially for early evaluation of QC platforms) is access via portals in the form of a QC-Platform as a Service (PaaS). Such platforms come with the potential of making algorithm development, job execution and documentation convenient, and transferable between the various computing systems. Several portals are available and under development throughout Europe. These platform focuses primarily on training, education, and the development of applications, so that more people can access QC technology as it develops.

Another more direct approach consists of controlling the QC system from the host via programmatic interfaces, which are then indirectly controlled by user programs on the host system. This option will be key for High Performance Computing - Quantum Computing (HPC-QC) integration, as discussed later in this document, and will enable the use of QC systems as true accelerators for applications. This opens up QC platforms for use in more complex applications and workflows, and offers the option of hiding QC elements for users in existing and well-established access patterns, as needed for industrial use cases.

iii. Commercial cloud access

Cloud access, including combined HPC-QC access from within clouds, is becoming an important business model to offer and commercialize QC platforms. However, currently, this is dominated by the large US cloud providers. It is important to strengthen the European footprint in this area, both by integrating QC resources into European cloud providers, and by enabling the use of European QC technologies in clouds world-wide.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Integrate quantum computers with classical computing systems like HPC supercomputers.
- Develop the needed programming interfaces (in the form of APIs and languages) to support easy access from developers. Novel approaches that require direct access from host systems to QC platforms, as this is key for HPC-QC integration, are needed.
- Significantly expand the availability of European quantum hardware in the commercial cloud offerings for general access, for example by creating a European platform, making it easy to benchmark and experiment with different types of European hardware and availability. This should target both EU clouds (availability for EU users under EU protections) and clouds world-wide (successful sales of EU QC systems).
- Availability of portal-based solutions for scientific access, to enable easy early experimentation and evaluation on the corresponding emulators.

1.1.B.6 Quantum algorithms

Quantum algorithms, unlike their classical counterparts, are designed to take advantage of the fundamental features of quantum physics, and unique aspects of quantum logic, represented in superposition and entanglement. A quantum algorithm consists of a sequence of elementary operations (gates) that change the state of the QCs. The sequence of gates performed on the qubits of the QC constitute a quantum circuit. Quantum algorithms are typically based on one of several fundamental primitives, such as Hamiltonian simulation, phase estimation, quantum search or quantum solvers of linear equations. Each of these primitives has resulted in several quantum algorithms.
More than half of the over 100 known QC algorithms offer super-polynomial performance improvements over classical algorithms. The development of quantum algorithms is also connected to the study of quantum information theory and quantum complexity, see also 2.1.A.3.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Build collections of use cases with reference implementations of quantum algorithms and data preparation.
- Develop new basic primitives for quantum algorithms, that would enable more quantum algorithm development.
- Develop new quantum algorithms providing speedups, especially for problems of relevance in science, technology and industry. Resource analysis regarding the number of qubits, number of gates, and estimated run-time should be conducted for each new algorithm.
- Build software that helps to develop and implement quantum algorithms, e.g., by automatically generating gate sequences or target Hamiltonians.
- Research methods on how to systematically tackle the task of developing quantum algorithms, including theoretical development and classical simulation.

1.1.C: Objectives and recommendations for quantum computation

Below we will summarise high level objectives and recommendations for the two main approaches of quantum computation, NISQ and FQTC, considering the main elements presented in the previous sections.

1.1.C.1 Objectives and recommendations for NISQ computing

Objectives and recommendations, short term (2024-2026)

- Develop hardware-agnostic benchmarking of NISQ based systems, quantum application and algorithm theory, software architecture, compilers and libraries, and simulation tools. These methods should make it possible to determine whether a given quantum algorithm run on a real NISQ machine shows any kind of practical advantage over state-of-the-art classical algorithms run on state-of-the-art classical hardware.
- Identify algorithms and use cases where quantum computing has an advantage verified through state-of-the-art cross-platform benchmarking on quantum and conventional computers. Provide rigorous performance guarantees for near-term quantum algorithms.
- Develop programming and verification interfaces to ensure correct by design circuit generation.
- Develop user- and system-facing access-APIs to enable multiple programming approaches as well as multiple back-ends.
- Support a modern compilation tool chain, which can combine static and dynamic optimisation as well as integrate with classical compiler infrastructures to natively support hybrid applications.
- Enhance the NISQ processing regime with error mitigation methods, enabling deeper algorithms, and integrate needed circuit transformation into compilation passes.
- Enlarge Europe's commercial quantum tech ecosystem by bringing on board chip foundries and other hardware providers, public or industrial, as well as the software industry, existing companies and a new cohort of start-ups. Foster close collaboration between hardware and software providers. Foster the development of co-design hardware and software which is tailored to specific applications.
- Continue academic and industrial research contribution on quantum device physics, qubit and gate control, leveraging optimal control theory for faster and more robust gates, photonics, RF-electronics, cryo- and superconductor electronics, system engineering, integration, device packaging.
- Integrate QCs with conventional computing systems like HPC supercomputers.
- Coordinate industry, foundries, and other infrastructure entities on quantum computing.
- Stimulate EU-wide joint actions with other fields such as material science, theoretical physics, cryo-physics, electrical engineering, mathematics, computer science and high-performance computing.

Objectives and recommendations, medium term (2027-2030)

- Demonstration of quantum processors fitted with error mitigation, and robust qubits with a universal set of gates.
- New quantum algorithms with smaller resource requirements that fit the available NISQ hardware.
- Develop new algorithmic primitives that would enable quantum algorithm design for a variety of problems and application areas.
- Demonstration of quantum algorithms with quantum advantage.
- Coordination of research, development and hybrid/hetero integration on materials, quantum device physics, qubit and gate control, quantum memories, photonics, RF, cryo- and superconductor-electronics, system engineering and device packaging.
- Develop an integrated tool-chain (design to processing) and module libraries for integrated optics, cryo- and superconductor electronics, including coherent optical-electronic converters, establishing foundries able to manufacture the required technology, including integrated photonics, cryogenic and superconducting electronics.

1.1.C.2 Objectives and recommendations for fault tolerant quantum computing

Objectives and recommendations, short term (2024-2026)

- Demonstrate practical error correction and a logical qubit: break-even (i.e. logical fidelity is better than fidelity of any of the underlying physical qubits) and below threshold (i.e. logical fidelity improves when the number of physical qubits increases).
- Evaluate integrated photonics and electronics technologies that exhibit high potential for both scaling and operation in cryogenic conditions.
- Provide reference hardware implementation of 1st generation error-correction decoders, to ensure the absence of scalability bottlenecks.
- Build system models of FTQC for various qubit technologies, to understand the dependency between all hardware to software constituents and identify practical scaling strategies to be further investigated.
- Secure first scalable cryo-compatible integration techniques, from which to build future co-integration strategies between control, qubits, and readout.
- Invest in experimental thermal decoupling strategies in cryogenic conditions, to provide deeper understanding of heat transfer in these conditions.
- Invest in VLSI test equipment providing statistical characterization in cryogenic conditions.
- Secure a reference open-source solution for room-temperature electronics necessary to keep investments in experimental quantum facilities throughout EU manageable while scaling.

Objectives and recommendations, medium term (2027-2030)

- Identify a scale-in roadmap for large scale quantum based on FTQC system models enriched with characterization results from proven technologies.
- Demonstrate a universal set of logical gates, i.e., the possibility to perform any quantum operation between logical qubits.
- Demonstrate practical implementation of all constituents necessary for the scaling of number of qubits and their control chain.
- Reach correct-by-design electronics development flows in cryogenic conditions, thanks to generated knowledge from characterisation, and the definition of adapted Electronic Design Automation (EDA) tools for the domain.
- Provide efficient quantum circuit transformation software solutions, enabling building guaranteed bridges between user-level "logical qubits" to physical qubits and code-correction supporting technologies.
- Integrate techniques for FTQC into the quantum software stack, its compilation tool chain and its programming abstractions.
- Demonstrate large-scale quantum processors fitted with quantum error correction and robust qubits with a universal set of gates, to outperform classical computers in terms of scale and speed-up.
- Integrate FTQCs with conventional computing systems like HPC supercomputers.
- Develop new algorithmic primitives and methods for quantum computers opening up new application areas in optimization and machine learning.

1.1.D: Hybrid HPC - Quantum Computing and Simulation

This section is common to Computing and Simulation. It is consolidated for both chapters, and presented in section 1.2 D

1.2

Quantum Simulation

1.2.A: Impact, societal challenges and quantum opportunities

Quantum simulation is the determination of physical properties of quantum systems, such as molecules or crystals, by calculation methods or by studying a different quantum system with similar properties (as opposed to a direct measurement on the system of interest). Due to the complexity of quantum mechanics, it is very hard to calculate these properties on classical computers, and impossible to carry out exact calculations for systems consisting of more than about 30 particles. Carrying out the calculation on a digital quantum computer is possible in principle, but in many cases the number and quality of qubits available in NISQ machines is insufficient. For many systems of interest, it is also hard to determine these properties experimentally, as the system is difficult to manipulate. This is where quantum simulators come into play. These are quantum devices that exhibit similar properties to the systems of interest but are easier to manipulate. On these machines, the properties of interest are in many situations determined in an analogue fashion, which is why quantum simulators are often also called “analogue quantum computers”. They are not universal computers, however, and can only be used to study problems following the same mathematical formalism as the actual quantum system implemented in the device. Nevertheless, there are many useful applications for quantum simulation, including basic science, materials research, quantum chemistry, and other areas.

It is easier to build analogue quantum simulators with high numbers of qubits than it is for digital gate-based quantum computers, as the requirements on qubit quality are somewhat less stringent for analogue devices. We can therefore expect suitable problems to be solvable earlier using quantum simulators. On the other hand, quantum error correction is not available for analogue devices.

Potential applications for quantum simulation affect many areas in which one needs to solve a challenging computational problem. It is however possible to identify three major computational categories in which an advantage is expected in the near future:

1. The simulation of complex quantum systems. Molecular and material simulations are computationally difficult to carry out on conventional computers. The quantum character of these simulations makes them potentially more suitable for a QC. It is an important goal to carry out proof-of-principle calculations on quantum simulators (QS), quantum annealers (QA) and variational hybrid quantum-classical algorithms on quantum emulators and NISQ devices. Future applications can be found in quantum chemistry and materials science, both in understanding the properties of molecules and materials and in designing them. Potential industrial applications can be found in, among others, the automotive (materials design for batteries), oil and gas, chemical (molecule and materials design, catalysts, fertilizers), photovoltaic and pharmaceutical (drug design) industries. Other future applications can for example be found in condensed matter physics, high-energy physics, particle physics, quantum field theory, and quantum biology.

2. Optimization. Optimization challenges comprise, among others, vehicle routing, power trading, supply chain network optimization, cancer radiation treatment scheduling, and optimizing target interactions for drug design. Optimization also lies at the heart of machine learning, artificial intelligence (AI), computer vision and data mining. In many practical optimization problems, the challenge is to find the best solution among a finite set of feasible solutions. Such problems are

formulated as discrete optimization problems.
Potential industrial applications comprise, among others, finances (asset management, portfolio optimization), insurance (risk optimization), travel (flight and train scheduling, hotel reservation), transport (vehicle routing, traffic flow prediction, tail assignment problem), logistics (scheduling), manufacturing (planning), energy supply (power trading and scheduling), the health sector (staff scheduling, organ allocation and acceptance optimization, cancer radiation treatment scheduling, treatment decision making) and the pharmaceutical industry (optimizing target interactions for drug design).

3. Machine learning is a branch of AI, which is based on the idea that computer algorithms can learn from data, identify patterns and improve their accuracy over time without being explicitly programmed to do so. Today, this technology is already bearing fruit and has spawned the field of so-called autoencoders, to speed up simulations, e.g., of turbulent flows, by large factors. Quantum-enhanced machine learning is a hybrid classical-quantum data-analytic technique that integrates quantum algorithms with classical machine learning. Examples are support vector machines (SVMs) for the classification and clustering of data, quantum reinforcement learning and the training of quantum Boltzmann machines. Potential applications are, among others, terrain classification in satellite remote sensing data, image-based medical diagnosis, forecasting in hydrologic research domains, and climate change prediction.

Different approaches to quantum simulation can be classified as follows:

Digital quantum simulators: they approximate quantum dynamics or more general quantum processing, by the application of different, sequential and/or parallel gates. Digital quantum simulators are therefore intrinsically programmable due to the approximation of the target dynamics starting from a few basic building blocks.

Analogue quantum simulators: they reproduce the behaviour of other interacting quantum systems under precisely controlled physical conditions. Because many computational problems can be mapped onto the dynamics of many-particle quantum systems, these devices can simulate complex systems of practical interest, such as complex networks found in industry settings. They go beyond a computational paradigm based on qubits, for example, by working directly with fermionic particles. This makes them less general, but significantly reduces the overheads and the requirements in terms of control.

Heuristic quantum devices: they aim at providing approximate solutions to optimisation problems. Examples are programmable quantum simulators, annealers, variational optimisers, or variants of quantum approximate optimisers and NISQ devices, which also play an important role for quantum computation. Here, often both a classical and a quantum component comes into play in hybrid schemes operating without QEC.

A strong effort is currently focused on exploring ways to approach quantum advantage by considering the analogue model of quantum computation. The algorithms that run under this paradigm can be based either on Adiabatic Quantum Computing (AQC) or annealing, which encode the solution of the problem in the ground state of the system's Hamiltonian, or on quantum simulation, which allows the system to evolve through its natural dynamics along all its possible states and codifies the solution as the state of the system after a given time.

The equivalence between the adiabatic and the gate-based models of quantum computation has been formally proven. Therefore, any quantum circuit can be mapped to a target Hamiltonian so that it can be solved via AQC and vice-versa, with a polynomial overhead in the computation time. The direct consequence is that, since the gate model is universal, the adiabatic model can be seen as a universal form of QC, assuming one can encode arbitrary Hamiltonians in the quantum device. The analogue simulation, on the other hand, targets specific problems typically based on the study of the dynamics of a physical system or its use for ML applications, as it allows for the processing of a larger amount of data due to the exponentially large space offered by the quantum nature of the qubits. The objective of a quantum annealer is to evolve the quantum system towards the ground state of the target Hamiltonian as in AQC. Problems suitable for quantum annealers include many industrial computing challenges involving finding effective solutions to large and complex optimisation problems. These problems may be found in sectors such as logistics, finance, the chemical and pharmaceutical industries, and materials science. Quantum annealers are therefore promising candidates for providing better-than-classical solutions to problems of this kind in the near future.

1.2.B: Scientific, technological and industrial challenges

In the following sections we will limit the discussion to the specific requirements of the different layers, and the system, for quantum simulation. All elements common to quantum computing have already been presented in the previous chapter, and will not be repeated below.

1.2.B.1 Physical platforms

In terms of hardware, the explored technologies have strong overlap with those discussed for quantum computation. A key difference is, however, that not all of them work specifically with qubits, especially when it comes to analogue simulators and heuristic devices. In many cases, the problem under consideration is naturally represented in terms of elementary quantum constituents living in spaces larger than that of a qubit (two-level systems), and a large number of qubits must be used to represent a single one, which should then be smartly interconnected to reproduce the interactions of the initial physical constituents.
By simulating the initial system directly with quantum elements living in Hilbert spaces of the same dimensionality, analogue quantum simulation reduces the physical resources required and the complexity of the problem.
It follows that quantum simulators, especially analog ones, are generally less sensitive to noise and decoherence. Hence, in particular, analogue simulators exploit the built-in complexity of many-particle quantum wavefunctions, turning it into computational advantage with respect to both classical and quantum digital processors with limited resources. This inherent aptitude to encode quantum complexity affords a favourable scaling of the required number of fundamental constituents and control capabilities for solving problems, e.g., in material sciences and quantum chemistry. This is generally natural when considering the quantum simulation of a quantum problem. For instance, the dynamics of correlated electrons is easily represented by an ultracold gas of fermionic atoms, whose internal as well as motional dynamics are similar. This asset has been successfully exploited to study a number of fundamental problems and better understand the properties of correlated quantum matter. In a nutshell, one main task consists in cooling down a system to find the ground state. This is nothing but an optimization problem, with potential applications to a countless number of optimization issues in many other fields, in any particular industry.
Quantum simulation can be implemented on a wide variety of complementary platforms, each with its own advantages and disadvantages.

Ultracold atoms and molecules

Ultracold atomic and molecular systems are an example of especially suited technology for analogue quantum simulation. Ultracold atoms are historically the ones that were used to perform the first quantum simulation experiments. Today, cooling and control methods make it possible to go down to temperatures a billionth of absolute zero, with ensembles of up to several millions of particles, and to control a large number of the parameters of these systems, including the strength of interactions.
These systems have already been successfully used to study a plethora of fundamental

properties of quantum matter in regimes beyond the reach of exact classical numerical methods. These include superfluid-insulator transitions, quantum magnetism, disordered and quasicrystal systems, topological phenomena, and low-dimensional quantum systems, to name a few. Quantum simulators using ultracold atoms have enabled us to gain a better understanding of the quantum behavior of matter. The applications to fundamental science are extremely vast, given the exceptional flexibility of these systems. One particularly interesting direction for instance, is to extend the simulation of electronic systems (fermionic by nature) to bosonic atomic analogues, which behave in radically different ways. This paves the way to the discovery of unexpected phenomena, not previously observed in traditional condensed matter systems, with potential applications to the development of new quantum devices that will exploit these properties and industrial development.

Traditionally, the field of ultracold atoms has been strongly focused on the simulation of systems relevant to condensed matter, but a branch is currently developing towards the simulation of high-energy physics, and in particular the elementary constituents of matter. This field is characterized by the interconnection of quantum physics and relativity. Beyond the fundamental aspect of understanding physics at the smallest scales, it may have long-term applications in the field of energy. To date, quantum simulation has largely enabled us to revisit known problems, particularly in condensed matter physics, either to observe for the first time phenomena predicted by theory, or approximate but relatively well-established classical numerical simulations, or to validate theories with more uncertain approximations. This has enabled us to bridge the gap between different disciplines, notably quantum optics, quantum information and condensed matter.

Compared to atoms, cold stable molecules offer new possibilities for quantum science: the presence of long-lived rotational states can be used to encode quantum information in the form of pseudo-spins (easily manipulable with microwave fields); with polar species, the strength and long-range nature of dipole-dipole interaction makes the molecular coupling effective even at moderate distances (hence yielding faster logic gates between remote qubits); the presence of hyperfine structure within a single rotational manifold can be used to realize four-level qudits (where quantum gates are implemented via two-photon microwave transitions); dipolar spin systems with anisotropic, long-range interactions allow to emulate a variety of quantum magnetism phenomena (e.g. antiferromagnets, valence bond solids, symmetry protected topological phases); combination with precision spectroscopy techniques enables new fundamental Physics tests (e.g. space-time stability of fundamental constants, parity violation, fifth-force searches).

Objectives and recommendations, short term (2024-2026)

- Carry out ab initio quantum simulations, without any initial theoretical knowledge. The ambition here is to move from a situation where theory motivates experiments to one where experiments play an exploratory role that will pave the way for the development of new theories.
- Develop and implement protocols for simulator certification, so as to ensure that the device simulates the problem under consideration in the absence of a priori knowledge of the result.
- Develop new methods for quantum simulation of fermionic systems. These are less amenable to classical simulation than bosonic systems. To achieve this, we need to develop new cooling methods that will enable us to reach even lower temperatures, deeper into the quantum regime. The challenge here is to gain between one and two orders of magnitude in temperature in fermionic systems to reach a sufficiently small fraction of the Fermi temperature.
- Develop new manipulation and detection techniques to increase the measurement rates (currently limited by the time needed for the preparation of the sample) and detection efficiency.
- Realize robust sources of cold stable molecules by adapting techniques developed for atoms (e.g. laser cooling and magneto-optical trapping) to molecular samples.

Objectives and recommendations, medium term (2027-2030)

- Develop general protocols for efficiently simulating useful use cases on ultra-cold atom simulation platforms. One potential application is optimization, where the central question is how to map a useful optimization problem onto the search for the ground state of a quantum system amenable to quantum simulation. Another is the possibility opened up by ultracold atom devices to simulate dynamical, i.e. time-dependent, problems, with potential applications to real-time control of nanodevices, or even fluid mechanics problems, which are particularly demanding in terms of classical computing time on large clusters.
- Increase technological readiness of atomic quantum simulators by improving their robustness toward maintenance-free, remotely controlled operation.
- Develop techniques for optical trapping cold stable molecules in their motional ground state to design new-generation molecule-based quantum simulators.

Superconducting

The most advanced quantum annealers available today are based on superconductors, solvers that use superconducting flux-qubit technology to solve certain optimisation problems. The limited coherence of the qubits and the architecture of the solvers mainly allow for the processing of quadratic unconstrained binary optimization (QUBO) problems embedded in an Ising Hamiltonian. Current flux-qubit proposals have longer coherence times and allow for richer control, even raising the possibility of encoding more complex Hamiltonian models than the Ising one.

AQC are an attractive alternative to quantum annealers, as they promise prospects for better exploiting the state of the art of superconducting qubit technology. These systems are based on high-quality qubits that offer much greater coherence when processing information using quantum tools. Consequently, AQC can go beyond QUBO problems and Ising Hamiltonians, enabling a broader set of challenges to be addressed and both types of adiabatic and quantum simulation algorithms to be implemented. Europe is already home to some leading companies on the full stack of AQC and superconducting qubit-based quantum simulators.

Objectives and recommendations, short term (2024-2026)

- Improve the coherence times of flux qubits by a factor of 10.
- Improve architectures to achieve better qubit interconnectivity and minimise encoding overhead.
- Implement non-stochastic couplings and chip configurations that go beyond the Ising model.
- Identify encodings that go beyond QUBO models (non-stochastic Hamiltonians).
- Foster research into the requirements for, and design of, universal annealing-based quantum computers, which have the potential to be direct competitors of fault-tolerant gate-based quantum computers.

Objectives and recommendations, medium term (2027-2030)

- First cloud-accessible superconducting qubit-based AQC in the world with 1000 qubits by 2030.
- Design and execution of benchmarks to assess and compare between quantum and classical computing paradigms in solving optimisation problems.
- Development of quantum ASICs for specific dedicated applications that allow a wide variety of Hamiltonians to be encoded, including quantum Hamiltonians.
- Further development on basic research into AQC with the long-term goal of designing and fabricating a universal AQC.

Spin qubits

The quantum computing section presents the current developmental status of semiconductor spin qubits. This section reviews research on applying spin qubits for use in quantum simulation applications.

There are still many issues to be overcome before we achieve a universal computer based on spin qubits; however, using subsets of the emerging technologies can offer interesting research opportunities. Some recent examples of research using early technology implementations include engineering topological states in atom-based semiconductor quantum dots, topological order detection and qubit encoding in Su–Schrieffer–Heeger type quantum dot arrays, and solving nonlinear differential equations with differentiable quantum circuits.

Spin qubits offer a natural, well-controlled, coherent and versatile platform for analog quantum simulation of Fermi-Hubbard physics, spin models, and quantum magnetism.

This platform is expected to reach the most interesting regime, where the thermal energy is far below the hopping energy, which in turn is below the on-site interaction energy.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- A key focus within the spin qubit research community at present is designs for universal quantum gate computers. Several companies are focusing on algorithms research and modelling of quantum systems with a view to running algorithms on universal quantum computers. However, it is also likely that new companies will emerge to take advantage of spin qubits and apply them in creative ways to solve quantum simulation problems.
- Design new simulation protocols tailored to spin qubit systems.

Trapped ions

One domain where trapped-ion computing is expected to come into its own is the broad area of optimisation and related problems that can be solved with AQC techniques. There are already industrial players in this field, using their platforms of microwave-controlled trapped ions. Application possibilities are widespread, ranging from portfolio optimisation in finance to waste minimisation in material cutting.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Efforts should be focused on tailoring and optimising annealing protocols to make full use of the intricate connectivity of microwave-controlled ions. Industry-relevant use cases should also be examined, first on small-scale quantum processors with a few tens of qubits, and subsequently with progressively larger, more capable quantum processors.

Programmable arrays of neutral atoms

Besides their application to quantum computing, individual atoms trapped in programmable arrays of optical tweezers realize a quantum simulation platform with native single-atom resolution. Excitation of the trapped atoms towards Rydberg states has enabled studies of quantum magnetism using a neutral-atom processors with approximately 200 spins operating in analogue mode. AQC based on neutral-atom can also be used to solve optimisation problems or perform quantum machine learning. Industrial solutions exist, using open-source Python libraries for emulating real quantum devices and controlling them at the laser pulse level.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Extend the library's capabilities, defining standards for processors based on programmable arrays of individual atoms. Connecting this library to other tools further up the stack is also essential.
- Extend the quantum simulation capabilities of these devices by increasing the number of spins, improving noise suppression, develop better schemes for coherent Rydberg excitation and high-fidelity detection.
- Develop certification processes in the absence of previous theoretical knowledge.
- Identify and implement useful use cases with a quantum advantage beyond fundamental science applications.
- Develop time-dependent quantum simulation.

1.2.B.2 Qubit control and programmability

As already discussed in the quantum computing sections, optimal operation of quantum computers requires the characterization and control of qubits.

Digital quantum simulators have similar qubit control requirements as quantum computers, although, depending on the specific problem, the universal set of individual qubit rotations and qubit-pair entangling operations can be replaced by a certain set of gates including global unitary operations. This renders qubit control capabilities in digital quantum simulators generally less demanding than in full quantum computers.

Analogue quantum simulators require a high precision of control, albeit not necessarily resolved at the individual constituent level, to precisely prepare target many-particle states and steer their quantum dynamics.

State-preparation fidelities and coherence times are also of central importance. The minimally realizable scale on quantum simulation platforms needs to be improved in order to widen the field of possible applications. This is relevant for applications for quantum problems in material design or quantum chemistry, as well as for optimization problems addressable by adiabatic quantum annealing.

Developing programmability of non-qubit based approaches is of central importance to make those hardware platforms more universal. This development must go hand in hand with the development of industry relevant applications of these simulators – application—hardware co-design.

Additionally, devising standardized benchmarks and verification protocols for analogue quantum operations, e.g., to characterize the coherence and the fidelity of quantum evolution in many-particle systems, is a central challenge to tackle in order to efficiently scale up analogue simulators to > 1000 qubits or fundamental units.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Devise effective benchmarking and certification protocols for problem-specific quantum simulators.
- Design digital twins of real world quantum simulators for benchmarking and verification.

1.2.B.3 Quantum APIs & cloud access

Quantum APIs and cloud access form the transition layer between users and quantum machines in the quantum computation stack. This layer includes general-purpose quantum SDKs that are used to implement quantum algorithms for both gate-based systems, AQC and quantum annealers.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Develop cloud-based integrations between different generalized API and software stack for analogue quantum simulators to address problems requiring a combination of resources.
- Improve availability of European quantum simulators in Europe-based clouds.
- Achieve integration of quantum simulators with HPC systems.

1.2.B.4 Quantum algorithms

In quantum simulation, a quantum algorithm may consist of the continuous time (natural) evolution of a quantum system to find the lowest-energy state of a system. Another important option is the study of dynamical evolution following a sudden change in external parameters (quench), that is particularly difficult to calculate on a classical computer.

Objectives and recommendations, short term (2024-2026) and medium term (2027-2030)

- Build collections of use cases with reference implementations of quantum algorithms and data preparation. This includes both slow (adiabatic) and fast (quench) evolutions, as well as regimes between.
- Design new algorithms providing speedups, especially for problems of relevance in science, technology and industry. Develop programming environments that allow users to encode their problems into the often very specific requirements of quantum simulators, such as QUBOs (quadratic unconstrained binary optimization problems).
- Build software that helps to develop and implement quantum algorithms, e.g.' by automatically generating (digital) gate sequences or tailored (analogue) quantum dynamics.
- Develop prescriptions for the embedding of hard optimization problems into specific quantum simulation physical platforms with proven quantum advantage.

1.2.C: Objectives and recommendations for quantum simulation

Objectives and recommendations, short term (2024-2026)

- Demonstrate the "quantum advantage" in simulation for a range of applications. This can be seen in terms of "supremacy" (perform useful tasks that are not realizable with classical machines), computation time gain, resource gain or energetic gain.
- Improve levels of control and scalability, and further reduce entropy in various platforms.
- Increase degree of programmability in various platforms to enlarge the addressable class of problems, identifying promising applications in concert with end-users.
- Allow for automated transformation of a problem from one platform to another to increase portability.
- Develop quantum-classical hybrid architectures to allow quantum simulators to address industry and R&I-relevant applications.
- Improve the control, scalability, quality of quantum simulation hardware, and its integration within HPC clusters.
- Develop the quantum simulation software stack and quantum-classical hybrid architectures.
- Expand and strengthen the supply chain and the development of key enabling technologies.
- Initiate certification and benchmarking of the most promising quantum simulators, for each device and/or in synergy of complementary devices.
- Foster access to quantum simulators by industry end-users and start-ups.
- Support co-design / co-development of quantum simulators between industrial end-users and quantum manufacturers (hardware & software) to accelerate work towards the demonstration of "quantum advantage" for industry-relevant purposes using quantum simulators.

Objectives and recommendations, medium term (2027-2030)

- Expand the relationships to end-users and develop more practical applications.
- Design error mitigation techniques tailored to analogue quantum simulators.
- Develop quantum simulators offering a higher degree of control and programmability.
- Build a bridge between industry and research on quantum simulation to translate the problems of industry in the language of simulation paradigms.
- Provide general methods for the certification and benchmarking of quantum simulators.

1.2.D: Hybrid HPC - Quantum Computing and Simulation

Quantum computer engineering has moved from a discipline within physics to become a multidisciplinary field addressing the entire stack from the quantum hardware at the bottom to the abstract mathematical formulation of quantum algorithms for solving particular classes of use-case problems at the top, with several layers of device, systems, and software engineering in-between.

As quantum computers and simulators (QCS) mature, their potential to accelerate solutions for key, particular, real-world academic and industrial problems where classical computing falls short to solve or scale becomes apparent. Also more evident is their limited ability to address practical problems when operated as stand-alone systems. Realizing the full potential for practical QCS then requires integration into classical computing, particularly HPC systems. QCS need to develop both into (i) HPC-centric accelerators for existing workflows managed by the HPC system that perform needed non-quantum computing tasks in the hybrid HPC-QCS infrastructure (either loosely coupled in modular component workflows or tightly integrated into a single program or close-feedback approaches) and (ii) QCS-centric “free-standing” QPUs supported by powerful classical pre- and post-processing resources in the QPU stack. In both cases, QCS can be used to accelerate solutions to key problems while running in concert with existing, established, and widely used classical algorithms and applications.

To complete the HPC-centric envisioned architecture, it is essential to understand how QCS can be integrated into HPC systems to work as accelerators in hybrid quantum-classical workflows. This requires the development of interfaces, both application and system-facing, leading to a common software stack that enables driving QCS as accelerators. HPC as a mature field can influence and guide the development of QCS hardware and software. As quantum computing relies on its connection to classical systems, early integration efforts are necessary, even if computational advantages may take some time to realize. In HPC-centric approaches, co-location and direct connection of prototype QCS systems and HPC systems/capabilities is not only relevant for the creation of a critical mass of multidisciplinary HPC and QCS workforce but can also be instrumental towards designing future hardware and software stacks that can support research on topics like algorithms with tight feedback loops, single hybrid system images and work towards error correction. The latter is also relevant for QCS-centric approaches where proximity between QCS and HPC systems is not the solution. However, hybrid QCS-centric and HPC-centric approaches may be warranted because different algorithms and applications will have different requirements on the balance between classical and quantum computing algorithms and on the required feeds and speeds.

To keep Europe at the forefront of conceiving, developing, and commercializing quantum technologies, the European Commission established in 2018 a large-scale research and innovation initiative known as the Quantum Flagship, with the declared long-term vision of creating a quantum internet, a network interconnecting quantum computers, simulators and sensors and distributing information to secure our digital infrastructure.
In 2018, Europe also established the European High Performance Computing Joint Undertaking (EuroHPC JU), a joint initiative between the EU, European countries, and private partners to develop a world-class supercomputing ecosystem in Europe. The EuroHPC JU enables European member states to coordinate their supercomputing strategies and investments

together with the EU with the objective to further develop, deploy, extend, and maintain a world-class supercomputing and data infrastructure in the EU, ranging from petascale to exascale and based on competitive European technology.
The EuroHPC JU, which enables the pooling of EU and national resources in HPC, contributes to the ideas and actions presented in the European Commission's Communication on Shaping Europe’s Digital Future. The development in Europe of a competitive HPC ecosystem (from technology components to systems and machines, and to applications and skills) and an integrated world-class exascale supercomputing and quantum computing capability will be crucial. It will provide Europe with leadership-class supercomputers and will ensure the EU maintains a leading position in the digital economy. It will also contribute to strengthening its technological and data autonomy. In this context, the EuroHPC JU formulated various ambitious goals for 2021-2033. Two of these goals are related to the deep integration of quantum computing and HPC, namely to develop and deploy a quantum computing and quantum simulation infrastructure integrated with the HPC infrastructure that is expected to make it possible to substantially accelerate the computing capacity of some of the European supercomputers, including some of the EuroHPC JU ones, and to federate European supercomputing and quantum computing resources making them accessible to a wide range of public and private users everywhere in Europe, including the European public data spaces, as presented in the 2020 European Data Strategy.

In order for the HPC supercomputing infrastructure to integrate QCS into a European infrastructure and to substantially enhance the computing capacity of some of the European supercomputers, a white paper was published in 2022 with a planned update in 2024, representing the view of both the HPC and the quantum communities. It presents the main challenges and recommendations for efficiently integrating a quantum accelerator in the HPC, including a roadmap for QCS deployment into a European quantum computing and simulation infrastructure named EuroQCS.
The aim of EuroQCS, which is at the boundary of EuroHPC JU and the European Quantum Flagship, is to become a federated European infrastructure for hybrid classical-quantum computing with remote access to QCS devices. EuroQCS will unify access to a variety of HPC and QCS resources that are co-located and deeply integrated in supercomputing centres or to stand-alone systems accessible via the cloud or connected to the supercomputing centres through classical network links in a first stage, and infrastructure developed by EuroQCI in the long term.

1.2.D.1 The first European project for hybrid integration: the European pilot <HPC|QS>

In 2021, work has begun on the EuroHPC JU “Pilot on quantum simulator” project <HPC|QS>. The aim of <HPC|QS> is to prepare European research, industry and society for the use and federal operation of QCS. <HPC|QS> is developing the programming platform for the QS, which is based on an emulating platform provided by a Europen company, and the deep, low-latency integration into modular HPC systems based on ParTec’s European modular supercomputing concept. . A twin pilot system of QSs, developed as a prototype by a European compan, will be implemented and integrated at CEA/TGCC (France) and Forschungzentrum Jülich/Jülich Supercomputing Centre (Germany), both hosts of European Tier-0 HPC systems. The pre-exascale sites BSC (Spain) and CINECA (Italy) as well as the national Quantum Learning Platform at ICHEC (Ireland) will be connected to the TGCC and Jülich Supercomputing Centre via the European data infrastructure FENIX.

1.2.D.2 EuroHPC JU's program establishing hybrid HPC-QCS systems

Following a call for expression of interest (EUROHPC-2022-CEI-QC-01) for hosting and operating European QCS integrated in HPC systems, launched in March 2022, EuroHPC JU has selected, in October 2022, six sites across the EU: IT4Innovations (Czechia), LRZ (Germany), BSC (Spain), Genci/CEA (France), Cineca (Italy), and PSNC (Poland). This program will be further expanded to include a joint development program for hybrid integration between the six sites with the goal to develop a joint European Quantum software stack.

1.2.D.3 Hybrid integration efforts as part of the EU Quantum Flagship Program

Both the newly started OpenSuperQPlus and Millenion projects of the Quantum Flagship include significant efforts toward integrating the newly developed quantum computing systems into HPC systems at multiple sites. Both projects rely on finding synergies with on-going and upcoming regional, national and European projects targeting HPC-QC integration.

1.2.D.4 National and local initiatives to support HPC-QCS developments

Several national and regional initiatives specifically target HPC-QCS integration. With a spectrum of approaches – from modular to more integrated, for example – the European HPC-QCS ecosystem leverages these efforts to strengthen its technology base and its position on a global market.
While not exhaustive, some examples include, in alphabetical order, :

Hybrid Quantum Initiative (HQI): Stemming from the French National Quantum Strategy announced in January 2021– along with other initiatives in quantum communication, sensors and enabling technologies– HQI is led by CEA, GENCI and Inria and aims to address the hybridization between HPC and quantum computing and simulation technologies. HQI consists of an HPC-QCS platform with various QPU technologies coupled to CEA-TGCC's Joliot Curie supercomputer and then to France's future EuroHPC exascale system; a broad academic and industrial research program that looks at the actual HPC-QCS coupling from a holistic perspective, ranging from system integration to hybrid end-user applications, as well as more exploratory topics such as noise characterization and mitigation or the use of quantum links for scaling; a dynamic dissemination (including hackathons) and end-user support program. HQI is fully integrated with European initiatives such as HPCQS and EuroQCS-France, and works with other EuroHPC JU Hosting Entities through a joint integration program.

ICSC National Research Centre for High Performance Computing, Big Data and Quantum Computing: The High-Performance Computing, Big Data e Quantum Computing Research Centre, created and managed by the ICSC, is one of the five National Centres established in Italy by the National Recovery and Resilience Plan (NRRP), covering designated strategic sectors for the development of the country, including quantum computing and its integration in HPC centres. One of the ICSC centre's objectives is to promote the national development of quantum computing technologies, seeking to cover as far as possible the entire spectrum of activities that make up the development of quantum computers. To this end, the centre has launched a three-year project that started in September 2022 and is due to end in August 2025, the aim of which is to finance the construction of at least three different large and scalable quantum computers on Italian soil and to develop a complete software stack that will enable the integration of Italian prototypes with the supercomputing centres spread across the country.

JUNIQ: After a preparatory phase that started in 2015, the Jülich UNified Infrastructure for Quantum computing (JUNIQ) at Jülich Supercomputing Centre (JSC) jointly funded by the Government (BMBF), North-Rhine Westphalia (NRW) and the HELMHOLTZ Association, launched user operation in 2019. JUNIQ's mission is to provide German and European science and industry with cloud-access to various types of quantum computers and to run software emulators of ideal and real quantum computers on JSC's Exascale-class supercomputers. Right from its start, JUNIQ is at the vanguard of deeply integrating HPC and QCS at system level with lowest latency and highest data throughput taking advantage of the Modular System Architecture (MSA), developed in hardware-software co-design within the EC-funded series of DEEP projects since 2012. Today, JUNIQ can already integrate its quantum computing systems into JSC's modular HPC environment. With its unified development platform, JUNIQ will include NISQ systems, quantum simulators and quantum annealers. JUNIQ offers a continuously running call for projects (peer reviewed, about 25 projects per year) together with pertinent support through its Simulation Lab for Quantum Computing to realize hybrid quantum HPC applications on the integrated systems.

Munich Quantum Valley (MQV): The MQV drives forward the development and maturation of several regionally derived QC technologies and unifies them via a common software stack tightly integrated into the HPC portfolio. Funded by the Bavarian Hightech Agenda along with several German BMBF and BMWK demonstrator projects and the EU Quantum Flagship projects OpenSuperQplus and Millenion, the Leibniz Supercomputing Centre (LRZ) of the Bavarian Academy of Sciences and Humanities spearheads development of a first truly hybrid quantum software stack combing the HPC and the QC environments into a single system, and the physical integration of HPC and QC systems from the control logic upwards. For this purpose, the LRZ has established the Quantum Integration Centre (QIC) providing co-location of QCs with multiple modalities (currently superconducting and ion-trap with more planned) in the same room as a state-of-the-art HPC cluster. The project also co-locates large-scale superconducting systems directly with LRZ's flagship HPC systems, enabling tightly integrated hybrid operations of QC systems as HPC accelerators.

Quantum Inspire: Quantum Inspire, the first European Quantum Computing cloud with 2 publicly available European built Quantum Computers was launched in April 2020. Shortly after, Quantum Inspire became part of the Dutch National Agenda Quantum Technology, a 630 MEuro program to accelerate quantum technology. Quantum Inspire is also part of the the EuroHPC program LUMI-Q and will connect the Dutch and other Quantum Computers to the LUMI network. IT is also part of the European flagship projects OpenSuperQplus and QLSI (and its successor QLSI2) to establish quantum computers with 100+ qubits based on both superconducting (transmon) and semiconducting (electron and hole spin qubits in SiGe) and connect them the national and European HPC infrastructure. The project also includes the co-location of classical and quantum computation resources to provide low latency hybrid classical-quantum algorithm execution functionality.

Quantum Spain and EuroQCS-Spain: Spain's national quantum computing initiative, Quantum Spain, is a 22 Million Euro project funded by the Ministry of Economic Affairs and Digital Agenda with the NextGeneration European Funds. The project started in October 2021, ends in December 2025, and is coordinated by the Barcelona Supercomputing Center (BSC-CNS). There are 27 institutions involved in this project: 14 from the Spanish Supercomputing Network and another 14 institutions experts in quantum computing. The main goal of

Quantum Spain is to encourage a strong and long-lasting quantum computing ecosystem in the country by deploying a quantum computing infrastructure which access will be public through the Spanish Supercomputing Network. Following the goals of Quantum Spain, the project EuroQCS-Spain aims to integrate the EuroHPC-JU quantum computer with the rest of the Spanish hybrid infrastructure, i.e. the BSC-CNS will offer supercomputing services with the MareNostrum5 supercomputer and integrate both Quantum Spain and EuroHPC-JU quantum computers to this infrastructure. This integration will be carried out by developing the necessary workflows to distribute the hybrid algorithms across all quantum and classical partitions. To that aim, the runtime developed by the BSC-CNS called COMPSs will be adapted to also operate on quantum computers.

The Nordic-Estonian Quantum Computing e-Infrastructure Quest (NordIQuEst): NordIQuEst, established in 2022, is a project funded by the Nordic e-Infrastructure Collaboration (NeIC), an organisational unit under NordForsk. The purpose of the project is to build a Nordic-Estonian e-infrastructure which combines high-performance computing and quantum computing resources and expertise from across Norway, Sweden, Denmark, Finland and Estonia. Efforts focus on development of a flexible QC-centric Nordic ecosystem cross-connecting QCs and HPC installations across the Nordics. To date, two QCs in Sweden and Finland have been connected to the pan-European LUMI pre-exascale supercomputer hosted in Finland. NordIQuEst is a leading effort towards a mature, distributed HPC-QC infrastructure in Europe. For example, cross-border HPC-QC jobs have been run on the infrastructure since 2022. Future efforts plan on expanding this with necessary local HPC resources directly connected to the quantum computing system, while larger classical resources can be connected remotely.

The Finnish Quantum-Computing Infrastructure (FiQCI): Building upon previous initiatives, FiQCI was formally established in 2020, when it became part of the Finnish Research Infrastructure (FIRI) roadmap of significant national research infrastructures, maintained and partly funded by the Research Council of Finland. FiQCI is operated and developed by VTT, Aalto University, and CSC – IT Center for Science. The mission of FiQCI is to provide state-of-the-art hybrid quantum-computing services to the Finnish and European RDI communities. This includes providing a hybrid HPC-QC platform for developing, testing, and exploiting quantum-accelerated computational workflows. FiQCI provides access to several software simulators, including the Atos QLM and other GPU-accelerated emulators. FiQCI has fully integrated the Finnish Quantum Computer (Helmi) with identity management, resource allocation, user support, and HPC resources of the pan-European LUMI supercomputer. FiQCI is thus one of the most mature hybrid HPC-QC platforms in the world. Through a continuous call, projects requiring physical NISQ QC hardware resources connected to HPC have been running on FiQCI since 2022.

Wallenberg Centre for Quantum Technology (WACQT): WACQT is a 12 year (2018-2029) 150 million Euro research effort that places Sweden at the forefront of the rapidly expanding area of quantum information technology. The main projects are to develop a superconducting quantum computer with at least 100 qubits and to build a sustainable Swedish QHPC ecosystem. WACQT/Chalmers is a partner in NordIQuEst, OpenSuperQPlus and LUMI-Q, and is currently testing QAL 9000, a 25-qubit superconducting processor, that will also be part of a Swedish QHPC testbed.

1.2.D.5 Timeline of the European HPC-QCS infrastructure

2023-24 Quantum Flagship FPA/SGAs with intermediate scale (20 to 200 physical qubits) QCS prototypes ready

- Intensive exploration of use cases, leveraging of quantum programming environments, remote or on-premise access of various prototypes and pilot systems, preparation of applications for wider deployment.
- Support the break-even point development of applications towards quantum computing – if applicable – for algorithms practical exploitation of NISQ devices and use cases for hybrid calculations.

2024-25 Deployment of five European petascale and three pre-exascale supercomputers – potential European HPC-QCS nodes

2025-26 Deployment of two European exascale systems - potential European HPC-QCS nodes

2025 Testing phase with intermediate scale prototypes

- Enhance the NISQ processing regime with quantum error mitigation methods, enabling deeper algorithms
- Develop cross-hardware benchmarking of NISQ based systems, quantum application and algorithm theory, software architecture, compilers and libraries, as well as Electronic Design Automation (EDA) and simulation tools
- Design and implement infrastructure for rapid development, deployment, and validation of quantum and hybrid applications (Quantum DevOps)
- Identify promising applications to consolidate toward creating a first generation of applications based on NISQ devices
- Launch the European HPC-QCS infrastructure
- Demonstrate automated system control and tune-up

2027 Deployment and access to intermediate scale platforms

- Run first-generation applications based on NISQ devices on the European HPC-QCS infrastructure.
- Identify and benchmark HPC-QCS algorithms potentially outperforming best classical counterparts.
- Demonstrate use cases/applications that establish complex workflows employing exascale-class HPC systems and emerging novel quantum accelerators.

2030 Integration of large scale (> 200 physical qubits) platforms from Quantum Flagship full phase

- Demonstrate quantum processors fitted with QEC and robust qubits with a universal set of gates which aim to outperform classical computers.
- Expand suite of HPC-QCS algorithms for software and hybrid-platform benchmarking, including digital error corrected systems, and optimize compilers and libraries.
- Provide prototypes and applications that effectively employ hybrid calculations for carefully selected use cases. Demonstrate use of the hybrid quantum-HPC infrastructure with scalable complex workflows.

1.2.D.6 Challenges and recommendations for a hybrid HPC-QCS platform

Currently, computational tasks that should be suitable for future QCS systems are still performed by conventional HPC systems. The objective for interfacing HPC systems and QCS is, therefore, to leverage QCS as accelerators for HPC systems and applications for such tasks (HPC-centric). Additionally, in the short- and medium-term, it is necessary to provide direct access to QCS using HPC resources for fast pre- and post-processing to execute quantum algorithms and experiments (QCS-centric) efficiently. Targeted steps towards QC scaling is a necessary step for achieving HPC-centric benefits.

While HPC systems and infrastructures demonstrate advanced reliability, availability and scale, QCS are currently evolving and maturing through RDI actions in academia and industry. In recent years, development roadmaps for HPC and QCS show recognition of one other and increased interest in overlapping and merging to the benefit of the HPC and the QCS communities:

- The HPC community will add a powerful accelerator capability to its larger technology platform, learn from the integration and use of QCS resources for particular workloads, and apply those new capabilities to the benefit of HPC centres and its user base.
- The QCS community will benefit from HPC's long-standing expertise, resources, and services, including existing structures for user authentication and resource allocation, and supporting software for, e.g., quantum algorithm compilation, optimisation, and error mitigation. This leapfrog towards stable support infrastructure and operational logistics will accelerate the adoption of QCS in various existing and potential user communities.

Realizing the full QCS potential requires integration with classical systems to manage input/output, orchestrate large(r) workflows, and implement (part of) the algorithms unsuitable for quantum hardware. A hybrid HPC-QCS approach appears, therefore, to be a very promising route to follow, with HPC architectures managing the core workflows, performing the needed non-quantum computing tasks or the tasks that cannot be accelerated by QCS, and QCS acting as powerful accelerator hardware. Additionally, hybrid HPC-QCS systems will still be a step forward in solving difficult problems if stand-alone quantum systems cannot be scaled up sufficiently or for application subcomponents not suited for quantum processing. The potential application areas of such hybrid systems are vast and include finance, energy, oil and gas, aerospace, transportation, chemistry, pharmacology, materials design, health care and areas like optimization, simulation or machine learning. Availability of real-world use cases are then expected to trigger private investment in hybrid HPC-QCS solutions.

To tap into the full potentials of HPC-QCS, a broad user base will need to invest time and effort in developing new kinds of algorithms, programming abstractions and system software that can be used to address and solve important real-world problems. Underlying this user/software interaction, there is also the software/hardware interaction. Since low level software is hardware-dependent, and quantum hardware is currently implemented on a variety of physical platforms (including, but not limited to, cold atoms/ions, super-/semiconductors, photons) this software/hardware interaction will require the development of a full and layered HPC-QCS software stack, which is compatible with established HPC stacks and environments. Using a suitable interface layer in this latter stack, users can connect a wide range of software to any one of several QCS architectures within a single HPC environment.

Challenges

To integrate HPC and QCS, fundamental differences between the two computational paradigms need to be bridged. This can only be done successfully if all levels of the system stack – from hardware to application – are considered. What follows, then, is a first set of specific integration challenges to address in order to develop these hybrid platforms.
It is vital that efforts supporting co-development and synergies between HPC and QCS are actively encouraged and continued. Unnecessary competition for the same resources should be avoided, as this could hamper the development

of the European HPC-QCS infrastructure and risk harming European long-term competitiveness in both quantum research and HPC capacities. Success requires the six aspects highlighted in the table below.

<table>
<tr><td rowspan="4">Skills development
Interdisciplinary, cross-domain</td><td>Use-cases for HPC-QCS systems
Applications, algorithms, hybrid workflows</td><td rowspan="4">High-level support teams
End-user engagement, requirements gathering</td></tr>
<tr><td>HPC-QCS software and programming tools
Language support, programming models, compilers, optimisers, profilers, debuggers, software deployment and validation tools</td></tr>
<tr><td>Access provision for HPC-QCS systems
Resource allocation, multi-level schedulers, authentication & authorisation, interfaces, virtualisation</td></tr>
<tr><td>Deployment and operation of HPC-QCS systems
Data centre, power systems, cooling systems, communication networks, monitoring systems</td></tr>
</table>

Essential aspects to develop and exploit hybrid HPC-QCS systems

Use-cases for HPC-QCS systems

It is essential to identify and develop use cases that demonstrate the advantage and co-design of hybrid HPC-QCS systems by combining conventional HPC and emergent QCS systems. Such use cases are crucial to steer and validate the interfacing of HPC and QCS systems. This includes targeting applications and algorithms with hybrid workflows for problems such as simulation, search, optimisation, and machine learning, as well as using conventional HPC to model, evaluate, and control QCS systems.

HPC-QCS software and programming toolkits

Conventional HPC software development kits and programming tools are highly mature and comprise modular and interoperable language features, libraries, and runtimes for orchestrating, optimising, profiling, and debugging parallel workloads and workflows. The software capabilities to program QCS are presently highly underdeveloped in comparison. It is necessary to develop and/or extend HPC-QCS software and programming tools to match the toolset of conventional HPC software development.

Skills development

While some shared skills exist, HPC and QCS experts currently work mostly independently of one another. Going forward, developing suitable workforce and training programmes will be paramount to build interdisciplinary and cross-domain skills between HPC and QCS across science, engineering, systems, software development and programming, algorithmic and applications.

High-level support teams

Sufficient user support is key to facilitate competence development and lower the barrier for uptake of HPC-QCS systems. To achieve this, the stakeholders involved in all levels of the HPC-QCS system stack should cooperatively create a pan-European, distributed expert support structure. High-level support teams (HLST) should liaise with existing EuroHPC HLSTs for an inclusive engagement with European user communities across HPC and QCS. The HLSTs would also serve to gather requirements from the user community, guiding the development of the hybrid HPC-QCS systems. For sufficient user engagement, it is important that the HLST structure is widely distributed, providing local contact points for as large a portion of the potential user community as possible.

Integration at the hardware level

- Interconnection networks and connectivity between HPC and QCS systems (hardware and protocol);
- Interconnection with emulators for a smooth transition from experiments to production;
- Interface to different QCS devices (e.g., photonic and superconducting quantum devices);
- Quantum Error Mitigation (QEM) and Correction (QEC) systems;
- Unified memories covering quantum and classical states;
- Hardware monitoring and telemetry of hybrid systems.

Integration at the system software level

- Scheduling, from hybrid job submission to individual shot scheduling;
- Hierarchical resource management (at multiple levels, from applications to individual shots);
- Offload / data transfer and staging;
- Integration of error correction on QCS with HPC mechanisms (system level);
- QC resources allocation integrated with HPC centre management;
- Virtualization and multi-user support at the host and control software level.

Integration at the programming environment level

- Integration into a base language;
- Single source programming for hybrid HPC-QCS paradigms;
- Support offload models like in OpenMP;
- Set of libraries providing (initially basic) algorithms;
- Integrated debugging and performance analysis tools (likely coupled with

simulation) in user space / on host systems.

Integration at the application/workflow level

- Resource management (user/application level);
- Granularity of offload;
- Integration of error correction on QCS with HPC mechanisms (user/application level);
- Data transfer between HPC systems and QCS counterparts.

An additional challenge is the training of active researchers and users, as well as contributions to education within university curricula in computer science/engineering and computational sciences, to support early quantum literacy at least at the level of MSc and PhD. This should include not only efforts in programming quantum algorithms and applications, but also in building the host and control side, and in operating and deploying QCS as part of HPC solutions.

Objectives and recommendations by 2024-2026

- Prepare and launch the European HPC-QCS infrastructure.
- Prepare pan-European quantum computing & simulation centres of excellence.
- Establish a joint EU-wide system allowing access to both HPC-centric and QC-centric systems.
- Start to integrate and/or extend conventional HPC software stack components to seamlessly support and interoperate with QCS hardware and software components.
- Support the development of HPC-QCS integration technology (connectivity, middleware, and libraries) to enable the tight HPC-QCS integration in both HPC-centric and QC-centric approaches.
- Initiate developments to create open-source middleware, schedulers, compilers, and other open-source software tools for hybrid HPC-QCS systems, in line with the open-source software strategy of the European Commission.
- Support the development of software components, tools, runtimes and environments to ease the use of hybrid classical-quantum computing, targeting industrial quality and usability.
- Support the infusion of hybrid HPC-QCS best practices quantum software start-ups for their sustainable growth.
- Support the development of scientific software applications for the use of HPC-QCS in relevant scientific and technological fields.
- Engage the HPC and QCS communities to cooperatively develop and demonstrate use-cases on hybrid HPC-QCS systems.
- Promote EU quantum computing & simulation research and foster its outcomes and applications in the EuroHPC JU and EU/national computing centres.
- Foster the uptake of key enabling technologies for quantum computing & simulation.
- Develop training mechanisms to build a European workforce with interdisciplinary and cross-domain skills to develop and use hybrid HPC-QCS systems.
- Disseminate EU technology achievements, contribute actively to the definition and emergence of global standards that are relevant, practical and useful for HPC-QCS systems and their use.
- Establish a well-defined framework to support increased collaboration and knowledge transfer in the European HPC-QCS ecosystem between related Digital Europe and Horizon Europe Programmes, particularly to synergize the developer and user communities across member states.

Objectives and recommendations by 2027-2030

- Support open-source developments to create operating systems, languages, compilers and software tools for HPC-QCS systems.
- Promote and monitor the development and deployment of quantum computing & simulation.

1.3

Quantum Communications

1.3.A: Impact, societal challenges and quantum opportunities

The area of quantum communications aims at designing hardware, tools and protocols to exchange quantum information among distant users. The carrier of quantum information for quantum communications is light. Within a general progressive vision of quantum communication networks, where increasingly complex hardware and software give rise to more advanced functionalities, the field can be presently roughly structured around the following directions:

(1) Technology focusing primarily on secure communication networks enabling applications such as quantum key distribution (QKD) and other protocols attainable at a similar stage of functionality, over point-to-point and metropolitan scale links. For some applications, this technology has reached high TRL, and commercial products have already been brought to market; however, significant challenges remain with respect for instance to integration and interoperability aspects;

(2) Research and development to unlock all the benefits of quantum communication for users around the globe, specifically enabling quantum communication over long distances, and offering higher stages of functionality to the users, based on the distribution of entangled states.

The overarching vision is to develop a Europe-wide quantum network that complements and expands the current digital infrastructure, laying the foundations and providing technological advances for a Quantum Internet.

To achieve this, the objective is to advance quantum communications in three essential directions:
1. Performance: Increasing bit rates, fidelities, link distances, deployment capability, and robustness of all types of quantum communications.
2. Integration and interoperability: Combining quantum communications with conventional network infrastructures and applications, cryptographic services, photonic and electronic platforms, and ensuring compatibility with quantum computers, simulators, and sensors.
3. Industrialization: Realizing technology that is sustainable, cost-effective, offers applications with a clear cost/benefit advantage in several sectors, and which generates wealth and jobs in Europe.

1.3.A.1 Point-to-point networks

The simplest quantum communication scenario corresponds to a point-to-point network consisting of two users. The main goal is to guarantee these two users can exchange quantum bits in a reliable way and to design novel or improved communication tasks exploiting the transmitted qubits. One of the main applications of quantum communications is the design of cryptographic schemes with security based on the laws of quantum physics. Secure communications play a vital role in the economy and society, as substantial amounts of data, with varying degrees of sensitivity, are transmitted daily and are used to perform critical operations (e.g. in government, healthcare, strategic and critical infrastructure). However, quantum computers pose a threat to current cryptography. Two alternatives could provide quantum-safe security: on the one hand, and not concerned with quantum communication itself, post-quantum cryptography (PQC) promises ways to secure data based on the hardness of specific mathematical constructions. On the other hand, QKD provides security based on quantum physics and requires quantum communications. Although different in nature and level of maturity, PQC and QKD offer complementary advantages, and hence are expected to co-exist and be used together in a quantum-safe and quantum-technology ready landscape. To this end, it can be strategic to design cryptographic protocols combining post-quantum and quantum primitives and produce corresponding software toolkits for an effective integration of PQC into quantum secure networks. This requires a strong synergy between the classical and quantum cryptographic communities with a strategic vision.

In practice, generating keys by QKD for secure data exchange and storage requires the existence of quantum communication channels, forming typically a network of fibre-based or free-space optical connections. Both types of channels have been successfully used, validating their functionality in principle. The driving parameter for QKD systems is the secret key rate shared by the users over a given distance. Despite QKD's attractive features, there is still room for improvement. Although recent schemes have demonstrated terrestrial QKD links of 800 km, in practice the communication range is still typically limited to metropolitan or regional area scales: for short ranges, less than 100 km, optical switches and fibre optic communications can be used to directly connect users. To further increase the communication range, presently and in the short term, trusted nodes are employed as relay. In the long term, long-distance quantum communication will require the development of quantum repeaters and satellite networks.

In the trusted node paradigm, information is processed classically in the intermediate nodes. Networks relying on such nodes hence place strong constraints in terms of operation and site security but are not limited in distance, in principle. They are relevant for sectors where such constraints are acceptable and are compatible with current technology, and for this reason they are widely deployed today. New architectural designs and protocols should improve the security vs. cost trade-off for such networks.

Intermediate paradigms in terms of the trust placed in the network nodes and deviating from the standard two-node/party point-to-point model, include protocols that relax some assumptions, such as, for instance, measurement device independent (MDI) and twin field (TF) QKD. In this case, a relay node containing an untrusted Bell state measurement setup is included in the implementation. Inversely, in entanglement-based QKD, the node emitting the entangled states can be considered untrusted. Ultimately, device-independent (DI) QKD relying on Bell non-locality has the capacity to minimize the security assumptions in the end user nodes as well. In general, techniques offering some form of device independence, even when some assumptions need to be maintained in practical cases in so-called semi-DI scenarios, are expected to offer flexibility and agility to functionalities: QKD but also quantum random number generation (QRNG), and beyond.

Other two-party protocols that can be showcased with point-to-point links include cryptographic primitives like coin flipping, oblivious transfer, distance bounding, or secure identification, which, contrary to QKD, belong to the mistrustful security framework (secure multi-party computation), where the two parties do not trust each other. Quantum secure direct communication is another cryptographic approach that allows direct transmission of secret messages without distributing private keys and classical cryptography.

1.3.A.2 Metropolitan networks

Moving beyond secure communication between two parties, we may consider more complex networks on the scale of a metropolitan area, that is, within a diameter of <50 km. At these distance scales, losses in optical fibres are sufficiently low that fibre-based quantum communication networks will be able to operate without quantum repeaters. To date, simple testbeds for such metropolitan networks have been realized. Multipartite metropolitan networks will enable secure communication to be provided as a service, mediated by central hubs that serve to connect users to one another. Also envisioned are the so-called 'prepare and measure' protocols, in which one network user prepares quantum states (known to that user) and sends them to any other network node, where a second user measures them.

Metropolitan multi-node networks offer perspective for testing architectures and network protocols for multi-user QKD via, for instance, point to multi-point links. Such testbeds can also be used to test the ability to support a big number of systems relying on different technologies (for instance, based on discrete or continuous variable encoding) and belonging to different domains with network orchestrators that allow connecting them and ensuring interoperability. Such tests will be crucial for the design, in the long run, of viable architectures for the European Quantum Communication Infrastructure (EuroQCI, see section 1.3.D) and instrumental for distributed quantum computing applications

.

Furthermore, going to more advanced applications in a multipartite scenario, a metropolitan hub will be responsible for preparing multi-qubit entangled states and distributing each qubit to a different network node, thereby establishing a link between those nodes. Verification protocols for such multipartite entangled states in adversarial scenarios have been developed and are the underlying element for a diverse range of quantum network applications, including conference key agreement, secret sharing, electronic voting, or anonymous communication. Note that combining QKD with secret sharing also enables long-term secure storage, which is interesting for securing long-lived data. Such applications can already be showcased in the relatively short term in metropolitan quantum networks.

1.3.A.3 The Quantum Internet

The long-term ambition is to realize a quantum communication infrastructure (or Quantum Internet) that can provide fundamentally new technology by enabling quantum communication between any two points on Earth. In synergy with the 'classical' Internet that we have today, a Quantum Internet will connect quantum processors to achieve unparalleled capabilities that are provably impossible using classical communication. The term internet refers to the ability to do inter-networking, in which smaller quantum networks in, e.g., metropolitan areas can be inter-connected to realize quantum networks on national, international, and global scales. It is anticipated that these networks will consist, on the one hand of a space backbone provided by satellites, and on the other hand, of optical fibre and/or free space links in which quantum repeaters are used to overcome the losses in long-distance channels. To achieve bit rates that are compatible with real-world applications, it will be necessary to multiplex the transfer and storage of quantum information across network channels, e.g., through the parallel encoding of quantum information at different frequencies. Realizing a fully-fledged quantum network requires advances in several key technologies. It will build on existing fibre-optic communication infrastructure but crucially will also involve the development of devices, infrastructure, methods, and protocols that do not yet exist. Above all, it calls for an interdisciplinary effort between physics, computer science and engineering. As with any radically new technology, it is hard to predict all uses of this future infrastructure, but several major applications have already been identified. One is to reach higher security level by enabling QKD with end-to-end security without relying on intermediary trusted relay nodes. These technologies will also enable the implementation of device-independent quantum cryptography protocols, where the level of trust on the implementation is minimal. Another straightforward application is the distribution of quantum information for other pillar-applications.

Progress towards a Quantum Internet may be measured along three axes: functionality, distance and accessibility (Figure 1.3.1). Functionality is a user centric way of measuring progress towards a Quantum Internet, which can be captured by stages of quantum network development (see Figure 1.3.2). Each such stage requires more sophisticated quantum hardware and software and offers more functionality and thus value to the user. Lower stages are thereby sufficient to realize, e.g., QKD, while higher stages enable the realization of more complex applications such as clock synchronization. Taking full advantage of a Quantum Internet at the quantum memory stage and above requires quantum processors as end nodes, capable of storing and manipulating quantum states. In contrast to quantum computing, the end nodes in a Quantum Internet do not need to manipulate large numbers of qubits. This is because many benefits of a Quantum Internet arise from its ability to distribute entanglement, and even entanglement between only two qubits at a distance unlocks benefits that are impossible to achieve using classical communication. This contrasts with quantum computing, where one needs a sufficient number of high-quality qubits in order to compete against classical supercomputers. Nevertheless, application protocols are known to showcase that additional benefits can be obtained by attaching quantum processors as end nodes that can perform fault-tolerant logical gate operations. With these capabilities in hand, a wide range of quantum applications become possible.

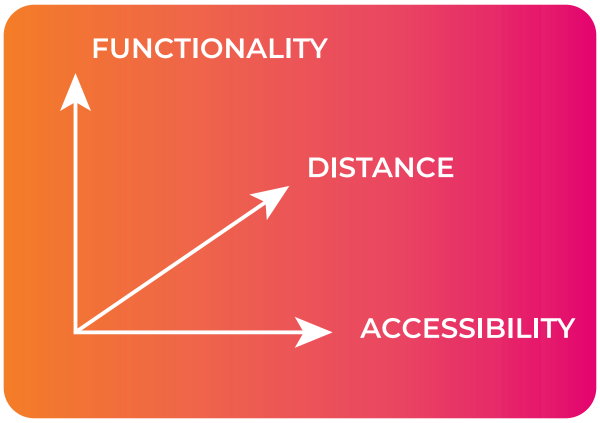

Figure 1.3.1: Progress towards a Quantum Internet can be measured along three axes.

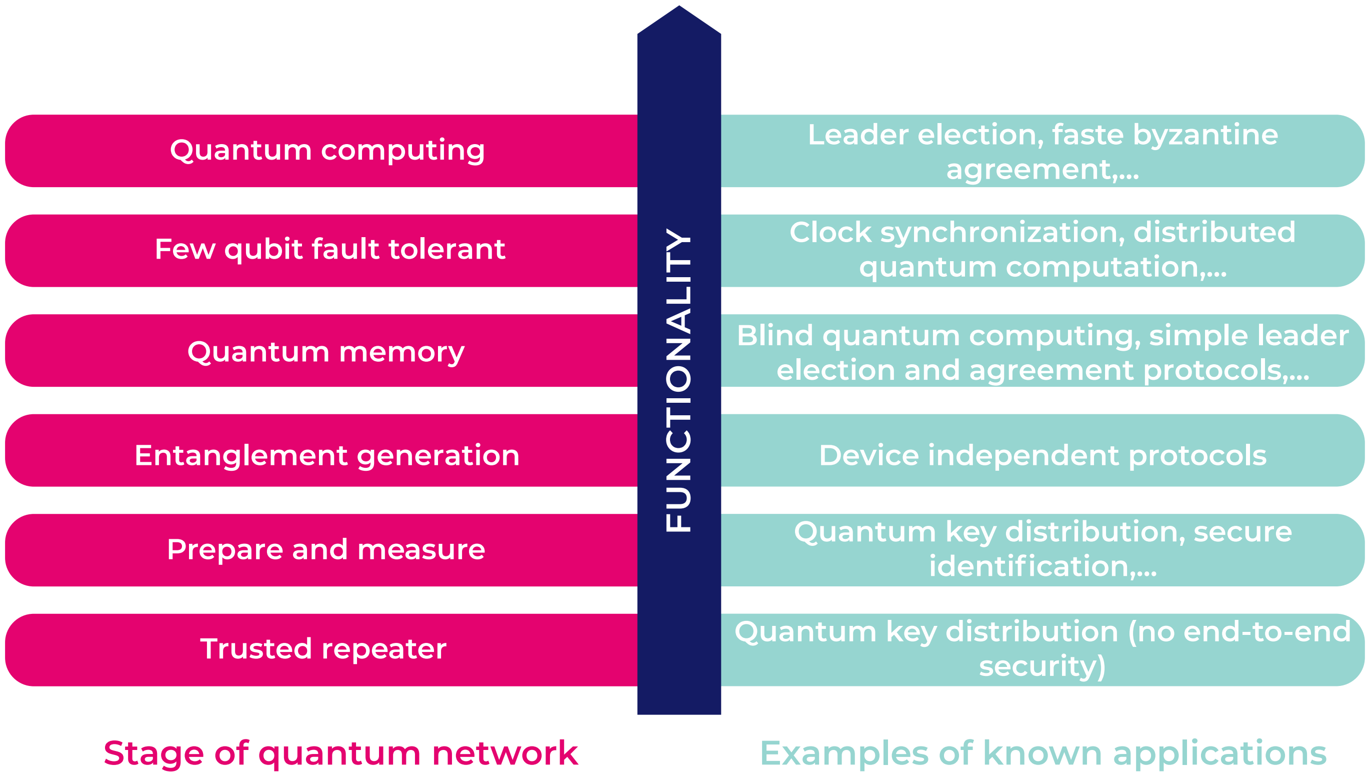

Figure 1.3.2: Example of functionalities (on the right) available when developping new hardware capabilities (on the left).
Source: https://www.science.org/doi/10.1126/science.aam9288

1.3.A.4 Other quantum network applications

Future quantum networks will link together other nascent quantum technologies, leading to novel applications. In the domain of quantum computing and simulation, quantum networks will enable distributed quantum information processing as well as secure access to remote quantum computers and simulators in the cloud (privacy preserving technologies). In the domain of quantum sensing and metrology, the quantum Internet will enable networks of quantum sensors, which will make it possible, for example, to extend the baseline of telescopes and to synchronize remote clocks, improving measurement accuracy and precision. Quantum network applications also extend to classical computing capabilities, where they will allow us to achieve efficient agreement on distributed data and secure multiparty computing.

Quantum networks have a wide range of potential use cases, that can be classified into stages of network development needed to support them. Examples of potential use cases are categorized into various fields of use which include Health and Health Care, Agriculture, Water and Food Supply, Energy and Sustainability, Security, Trading and Finance, and Mobility and Logistics.

1.3.A.5 Example use cases and applications

Below we list a few example use cases of quantum networks:

Functionality → Relevant Fields	**Description**
Prepare and measure stage	
Secure Communication and Authentication → Security, Agriculture, Water and Food Supply, Energy and Sustainability	Securing communication in transit and authenticating access are critical technical challenges. for critical infrastructures and sensitive information. Quantum networks have been investigated to prove that they provide better security compared to classical networks against attackers that may utilize quantum computing.
Password Identification → Security	Password Identification focuses on verifying passwords in cases where neither the server nor the client is trusted. For instance, securing password-based access to critical infrastructures, remote login to a bank or government institution with enhanced security, and securing access to home IoT devices. This application has been investigated to assess quantum networks security compared to classical networks.
Privacy-Preserving Analytics → Security, Health, Health Care	Privacy-Preserving Analytics enables computing functions on private inputs held by the client and server without revealing the data. with application e.g.in the pharmaceutical industry, where looking up illness symptoms in a remote database without revealing the symptoms is critical. It also allows for computing statistics on confidential governmental data about citizens without revealing the data.
Random number generation → Security	Quantum networks can generate unbiased random strings between clients and servers, which is essential for numerous applications: mathematics, simulations, fairness in online gambling.
Enhanced Security for Cryptocurrencies → Security, Finance	By using quantum-enhanced authentication, the security of cryptocurrencies and blockchain technology could potentially be improved.
Entanglement generation stage	
Faster Trading → Finance	In the entanglement generation stage, quantum networks can potentially beat the latency of direct transmission of information by using pre-shared entanglement, up to the limit that entanglement does not enable faster than light communication.

Quantum Memory Stage	
Secure Quantum Computing in the Cloud → Security, Health, Energy	At this stage, performing quantum computation on a remote quantum processor without revealing the program or user input, termed blind quantum computing or secure delegated quantum computing, becomes possible. This is of interest for the pharmaceutical and chemical industry to explore proprietary new materials or drug designs securely.
Keeping Data in the Cloud Consistent / Organize Access to Cloud Data → Security, Health, Energy, Mobility, Logistics	Quantum networks could accelerate real-world consensus and leader election problems, enabling faster data consistency across multiple sites for cloud service providers or medical industries
Quantum Enhanced Remote Sensing → Energy	Quantum networks can combine remote sensors, potentially enabling better resolution e.g. to achieve higher resolution astronomical images and in-depth ground sensing.
Few Qubits Fault Tolerant Stage and above	
Clock Synchronization → Mobility, Logistics, Trading	Quantum networks based on optical fibers could exploit established techniques for the transmission of time scales to any location and thus network synchronization with time instabilities of less than 10 ps for averaging periods between 10 s and 10 days. This technical capability can benefit detector and source synchronization, which is relevant to quantum communication but also impacts public sector applications with economic perspectives e.g. providing a secure framework of financial transactions and data transfer, where improving the accuracy of timestamps is critical.
Quantum Computation on Private Data → Security, Health, Energy, Mobility, Logistics	Quantum computation on private data addresses the technical challenge of secure multi-party quantum computation. For instance, within the pharmaceutical and chemical industry, it is possible to determine the compatibility of two proprietary new drug designs and materials in a quantum simulation without disclosing such designs. Another application is in private sensing, where the values of remote quantum sensors can be compared without revealing their readings. This technology has been investigated and is possible in principle, but the requirements for real-world applications remain unclear. This might necessitate the quantum computing stage if the computational demands are extremely high.
Faster Comparisons and Scheduling → Logistics	Faster comparisons and scheduling are possible by reducing the amount of communication required to solve specific tasks. This technology could revolutionize mobility and logistics through applications like faster appointment scheduling across multiple calendars or expediting comparisons of data stored at two different sites on a network. The feasibility of this technology has been investigated, but the requirements for real-world applications remain undetermined.

Faster Image Processing → Mobility, Logistics, Security	Faster image processing aims to reduce the amount of communication necessary for solving image recognition problems. This has potential applications in public image recognition (e.g., identifying if a person is on a wanted list) and can be used in autonomous vehicles or other agents. Though not yet investigated, protocols with exponential savings in reducing the amount of communication have been proposed for certain vector/subspace problems, which might be applicable here.
Machine Learning with Distributed Quantum Data → Energy, Agriculture, Mobility, Logistics	Machine learning with distributed quantum data deals with the technical problem of training machine learning algorithms using private quantum states. This has the potential to be employed in training machine learning algorithms on remote quantum sensor data while keeping the data private. Classical methods for training with classical data exist, and certain corresponding quantum methods are already known.
Unforgeable Money → Security, Finance	Creating unforgeable money involves storing monetary value in a quantum state. This can result in an unforgeable currency for online payments, enhancing security and facilitating mobility and logistics. While this has been investigated, the requirements for real-world application are not yet clear.
Digital Rights Management → Security, Mobility, Logistics	Digital rights management is concerned with making data accessible to a client only once. Examples include making data accessible only a single time or creating one-time quantum programs that can be run only once. While not fully investigated, theoretical protocols do exist (subject to various assumptions), but real-world use case examples and their requirements remain unclear.
Proof of Deletion → Security, Health	Proof of deletion involves a server providing a client with proof that hosted data has been deleted. For example, a cloud service provider can offer a certificate indicating that data was deleted from the cloud, or patients can be assured that their medical data has been erased. While protocols for this technology do exist, the specific requirements for real-world applications are yet to be established.

1.3.B: Scientific, technological and industrial challenges

The main physical components of a quantum network will be:

- ***Sources and detectors:*** quantum light generation, preparation and measurement of quantum states within a quantum network is an integral part of QKD and other network applications.
- ***Quantum channels:*** Within a quantum network, quantum states are distributed along quantum channels. Such channels may be in free space (e.g., for satellite communications) or through optical fibre.
- ***Optical fibre infrastructure:*** Optical fibres enable the transmission of quantum states with low losses at the infrared wavelengths used for telecommunications. Interoperability with existing networks, infrastructures and devices is a challenge.
- ***Satellites:*** For ultra-long-distance, satellites may be used to distribute entanglement between different points in the network, and can also serve as trusted relay nodes in prepare and measure protocols.
- ***End nodes:*** The quantum analogues of laptops and phones connected to the Internet. End nodes are required to enable the execution of quantum communication applications, and hence to make Quantum Internet technology available to end users. They can range from simple QKD devices to quantum computing servers.
- ***Quantum repeaters:*** To connect many users at national, international, or continental distances, a quantum repeater may be used to generate long-distance entanglement over fibre networks. Quantum repeaters mitigate the signal attenuation due to scattering and absorption losses in optical fibre. Quantum repeaters include quantum memories and Bell state measurement devices. Repeater nodes may include multiplexing capabilities as well as capabilities for entanglement purification and/or error correction.
- ***Switches and hubs:*** Photonic switches and hubs will allow signals to be routed within a quantum network, connecting and disconnecting end nodes with one another in a dynamic fashion.

1.3.B.1 Hardware challenges

From an implementation perspective, quantum communication requires the development of a diverse array of technologies to create, store, manipulate, and measure quantum states. In particular, the control and manipulation of light (photons), matter and their interaction are essential to attain a quantum-secure network and the Quantum Internet, and most generally to unlock delegated applications and combine devices to achieve enhanced functionalities for all quantum technology applications. These tasks will require the development, engineering, industrialization and commercialization of novel hardware to be used in every node of quantum networks, including:

- Non-classical photon sources with specific wavelength and bandwidth requirements to be compatible with quantum nodes and memories, as well as single-photon purity and efficiency specifications. The photon source may include single and entangled photon sources, as well as multiphoton entangled state sources.
- Photon detection technologies, both in the single-photon regime and for continuous-variable systems. While such technologies are currently available, it will be important to improve detection efficiencies and speed, to reduce background noise and crosstalks, and to develop modules that are cost-effective, have a small footprint, and can be deployed in the field. For example, the

most efficient single-photon detectors currently available at telecommunication wavelengths require a 1-4K environment, and thus a cryostat, for operation and as a result are very energy expensive. Another challenge is the development of photon-number-resolving detectors for enhanced efficiency and protocols. Coherent detectors are well suited for photonic integration but need to operate at low noise over a suitable bandwidth. Fast, stable, reliable and scalable control and time tagging electronics are required.

- Photon manipulation technologies can be active devices such as electro-optical modulators or passive ones such as, interferometers, filters, and splitters. In all cases these components must be improved in performance (lower loss, higher extinction, sharper transition edges, etc.) to comply with the stringent requirements of quantum communication applications.
- Quantum memories and interfaces between quantum information carriers (quantum states of light) and quantum information storage and processing devices (atoms, ions, solid-state systems). They are required for higher stage applications and come with the challenge of harnessing light matter interaction and matching bandwidth and wavelength together with engineering practical and cost-effective implementation. Quantum memories should feature high-efficiency and high-fidelity storage, as well as long storage times. Preferably they should include a multiplexing capability to increase the rate of entanglement distribution between remote nodes. For long distance applications, quantum memories should be linked to telecom wavelengths (e.g., through quantum frequency conversion or non-degenerate sources).

Below we detail hardware challenges related to different parts of envisioned quantum networks: the end user nodes, the links connecting them, the repeater nodes and higher-level components.

Finally, while most quantum communication protocols are phrased in terms of qubits, it is as well interesting to investigate quantum information encoded on d-level quantum systems, also called qudits. Being multi-level, the first and relatively straightforward advantage qudits offer is the increased information capacity per transmitted quantum system. It has also been shown that the use of qudits gives more robustness to noise. However, the manipulation and transmission of qudits is also more difficult from a hardware perspective.

i. End nodes

There are currently several candidate platforms for quantum-network end nodes. While great progress has been made in recent years, each platform faces challenges, particularly with regards to scalability. That is, small numbers of prototype end nodes are currently in operation in state-of-the-art laboratories, but it will be necessary to dramatically increase these numbers, and to deploy the end nodes for robust operation across a telecommunications network, e.g., within data centres.

Here, we discuss some of the most promising candidates and highlight their strengths and weaknesses. Let us emphasize that there will not necessarily be a single “winner”: just as laptops and phones have different, complementary roles when connected to the classical Internet, one can expect that a future Quantum Internet will contain a variety of end nodes, each tailored to specific applications.

- **Trapped atomic ions:** We have already seen that trapped ions are one of the leading platforms for quantum computing and simulation. It is possible to prepare, manipulate, and measure quantum states with record-high fidelities, and benefit from relative long coherence times as compared to the gate-operation times. These advantages are also important in the context of quantum networks: for the execution of network applications at end nodes, it is necessary to process quantum information, which must then be stored — potentially for long intervals — while communication links are established with other nodes. Equally important, transitions between electronic energy levels provide a spin-photon interface, allowing quantum information to be transferred between a qubit stored in an ion (which remains at the end node) and a qubit stored in an infrared photon (which travels along a quantum channel). In recent experiments, quantum frequency conversion has been used to convert the photon to telecommunication frequencies that are well-suited for long-distance networks, while preserving high-fidelity entanglement between the ion spin and the photon. However, trapped-ion experiments require ultra-high vacuum, which is expensive and time-intensive to assemble. Moreover, the trapped-ion spin-photon interface is slow with respect to other end-node platforms, that is, the length of the photons' temporal wave packets and the intervals required for quantum-state manipulation and readout are relatively long.

- **Trapped neutral atoms:** Like trapped atomic ions, trapped neutral atoms can be used to encode qubits (spins) within electronic energy levels, and optical transitions between those levels provide a spin-photon interface for quantum networks. As we have seen in earlier discussions on quantum computing and simulation, there has been remarkable progress in the past years on reconfigurable arrays of atoms stored in optical tweezers, and on quantum information processing with Rydberg states of those atoms. These achievements are promising for quantum-network end nodes: neutral atoms in tweezers offer both excellent quantum information processing capabilities and a photonic interface that, for commonly used alkali atoms, lies in the near-infrared regime. Indeed, quantum frequency conversion has been used recently to build elementary networks between neutral-atom systems separated by tens of kilometres of optical fibre. Meanwhile, atoms coupled to optical cavities have been used for landmark demonstrations of quantum networking protocols. Like trapped ions, neutral atoms require operation in ultra-high vacuum. And while the reconfigurability of neutral-atom arrays — in two and even three dimensions — is a significant advantage, there is a concomitant drawback: trap depths in such arrays are relatively shallow, meaning that it is challenging to store atoms for long periods of time, and during operations such as qubit measurement.

- **Colour centres in diamond:** The most well-studied colour centre in diamond for quantum information processing is the nitrogen vacancy (NV) centre. Here, a spin is encoded in the electronic states associated with a substitutional nitrogen and a missing carbon atom in the diamond lattice. Again, just as for ions and atoms, a transition between electronic states provides a spin-photon interface, in this case at a visible wavelength. Some of the most advanced quantum-network demonstrations to date have been implemented with NV-centre end nodes, including deterministic entanglement and teleportation across a three-node network. A particular strength is the high rate at which spin-photon entanglement can be generated. In addition to electronic spins for quantum information processing, colour centres can take advantage of nuclear spins as nearby quantum memories. Working in a solid-state platform has the advantage that colour-centre qubits do not need to be actively trapped: they are already trapped in the diamond lattice. However, these end nodes do need to be kept in a cryogenic environment. Furthermore, efforts to embed NV centres in photonic structures such as cavities — which will be crucial for scaling up these systems — have only had limited success, due to the reduced performance of the NV centres near surfaces. Group-IV defects in diamond, including silicon germanium and tin (SiV, GeV and SnV), currently appear to be promising for such photonic integration. These defects are less sensitive to electronic noise at the surface and are less coupled to phonons offering the majority of their emission in the useful zero-phonon-line.

- **Single rare-earth ions in solids:** Recent studies have shown that it is possible to detect and manipulate individual rare-earth ions (Eu, Er, Yb etc.) in solid-state samples embedded in cavities. This platform provides a spin-photon interface that can be potentially long lived and where many ions at different frequency can be addressed. The ions can interact with each other thanks to dipolar interactions (making possible two-qubit quantum gates) and are connected to photons via optical transitions, making it a promising alternative system towards quantum processing nodes. Rare-earth ions can be incorporated into bulk high-quality crystals or in thin films and nanoparticles. They can easily be substituted for one another, offering a wide range of transitions including in the useful infrared region. More investigations are needed to confirm the processing capabilities.

- **Superconducting qubits:** It is natural to look to superconducting qubits as potential end nodes, as they are leading candidates for quantum information processing, due both to the very high fidelities that have been achieved for gate operations and to the possibility to exploit well-established fabrication techniques as a path to scalability. Moreover, the high speeds of superconducting-qubit gate operations are promising for efficient implementation of quantum network applications. The major challenge is that superconducting qubits lack an optical interface and have very low coherence times, while applications for processing nodes in a quantum network often require long coherence times (of the order of ms) to execute. The transitions between energy levels in superconducting qubits occur at microwave, not optical, frequencies, and microwave propagation have high losses; it is not compatible with long-distance quantum communication. Thus, much effort is currently being directed towards microwave-to-optical interfaces that can preserve the quantum nature of states at the single-photon level.

ii. Links

To deploy long-distance links integrating quantum repeater and processing node technology managed by a full-stack control plane and giving access to advanced functionalities, it requires encompassing a diverse array of technologies, including the creation and manipulation of entangled states, the design of quantum memories, QRNG, QKD, potentially combined with PQC.

The demonstration of quantum repeater links over long distances will require high-performance quantum nodes. For protocols based on single-photon entanglement, which scale better with losses than other protocols, phase stabilization of the fibre links and between the remote nodes is needed. Also, a very high degree of multiplexing will likely be required to compensate for the transmission loss of long fibre links.

Performing quantum communication integrating all the above elements over free-space and satellite links puts significant additional constraints. Atmospheric and weather conditions can strongly affect the performance of free-space QKD links. Optimization of free-space channels via adaptive optics, channel optimization strategies, also based on AI, and optimal modulation strategies will guarantee stable and long-distance working conditions for QKD. Space-based links naturally allow for long distances due to light travelling through space for most of the trajectory, but the perturbations and fluctuations due to the atmosphere and the stringent constraints imposed on the characteristics of satellite payloads, make the design and implementation of satellite quantum communication challenging. Criteria that play an important role include operation wavelength for bandwidth and daylight or night time use, downlink or uplink path, orbit of the satellite and corresponding geographic coverage and loss budget, size of telescopes on the satellite but also on the ground depending on the application, space qualification of components and systems, site choice for ensuring availability, use of advanced techniques like adaptive optics for correcting wavefront aberrations and optimizing coupling to fibre infrastructure on the ground, etc. Although QKD has been shown to be feasible over such links and technology is progressively advancing, advanced network stages including quantum memories, repeater nodes, and end nodes, need to be first validated in terrestrial networks before considering their use in space conditions. Accurate simulation tools for assessing such networks may be helpful to drive technology to the most promising directions.

iii. Quantum repeater nodes

Near-term quantum repeaters will probably rely on architectures involving multiplexed heralded entanglement between remote nodes (first generation repeaters). For this approach, quantum repeater nodes should include an entanglement source, a quantum memory and be compatible with the fibre telecom network. Most of the end nodes described above could serve as quantum repeater nodes, if combined with a quantum frequency conversion stage. Another important point is that the nodes should be multiplexed to increase the entanglement rate at a distance. Ensemble-based approaches are particularly well suited for multiplexing. The main ensemble-based approaches for quantum memories are:

- **Atomic ensembles:** Cold atoms represent an advanced platform that has been for early demonstrations of quantum repeater links. The atoms are laser-cooled and trapped in an ultra-high vacuum chamber. This platform has demonstrated very high storage efficiencies (up to 90 %) and long storage times. Some degree of multiplexing can be achieved using mostly the spatial degree of freedom. Warm atomic vapours may also be used. They have the advantage of a simpler experimental setup, but storage times need to be increased for long distance applications.

- **Rare-earth doped solids:** This platform offers a large number of atoms with optical and long-lived spin transitions with exceptional coherence properties (at $T < 4$ K), in a solid-state environment. As with other solid-state platforms, the atoms are naturally trapped but need to be cooled down in a cryostat. Rare-earth doped solids offer a system for high-efficiency, high fidelity and long-lived quantum memories. A strong advantage is that the multiplexing capacity is very high since many degrees of freedom can be combined (space, time, frequency).

Entanglement sources used in current proof of principle demonstrations rely on probabilistic processes. Such sources should be improved and miniaturized. For the next generation of quantum repeater nodes with higher rates, quasi-deterministic single photon and entangled photon sources compatible with the quantum memories should be developed using, e.g., atomic or solid-state emitters.

Other quantum repeater architectures have been proposed, the so-called one-way repeaters, based on the generation of photonic cluster states and QEC. These repeaters promise in theory high transmission rates for qubits but require the generation of highly entangled multi-photon states containing hundreds of photons per node with very high efficiency and fidelity, and quantum repeater nodes spaced by only a few km. While this is challenging in the short term, research should be done to improve the generation of photonic cluster states. Promising platforms include single atoms in cavities, quantum dots, or massively multiplexed probabilistic sources.

In addition, other processing nodes platforms proposed at end nodes can also act as quantum repeater nodes. This includes colour centres in diamonds, ion traps and neutral atoms.

iv. Higher level components

High-level components are combinations of hardware and software that should be standardized so that they can be used as building blocks of quantum networks. In particular, we can mention:

- **QKD transmitter and receiver devices** and more generally photonic systems implementing quantum cryptographic protocols need to be miniaturized, energy efficient and scalable, which can be achieved with the development of quantum-grade photonic integrated circuits on a variety of platforms. System interoperability with the development of appropriate interfaces and coexistence with classical networks overseen by services orchestrating both classical and quantum resources will be crucial for practical use cases.
- **Switches and hubs:** Photonic switches and hubs will allow signals to be routed within a quantum network, connecting and disconnecting end nodes with one another in a dynamic fashion.
- **Processing nodes** in order to support advanced functionalities should be able to store and manipulate qubits. These nodes should have an efficient optical interface and coherence times long enough to support application protocols that require eventually several rounds of classical communication to be executed.

For these elements to be of practical use, they should be built with technologies that are able to scale to large numbers, for instance using photonic integration, and they should also be resilient enough to tolerate the harsh environments in telecommunication-network field deployments.

v. Enabling technologies

Below we list a few critical technologies specific to the Quantum Communication field:

Cryogen-free and closed-cycle compact cryogenic systems for 0.8-4K range
Several promising quantum hardware platforms require cryogenic cooling below 4K (typically around 1K). Many suppliers are available (also within EU-27) for such cryostats. However, they are designed for general purpose, have large form factors, are expensive and not optimized towards the specific needs of Quantum Internet hardware. Development of tailored, cheaper cryostats compatible with use in data centres and/or current telecom infrastructure is required.

Packaging for heterogeneous quantum network nodes
The best qubit devices for quantum networks currently exist in materials that are not the best photonic integration platforms. To combine the two towards industrial products, optimization of efficiency and development of reliable production process for such hybrid devices is required. This means especially the packaging side in near term calls, with photonic integration to be targeted in later rounds.

Robust, tunable low phase noise lasers
These lasers will be needed to address quantum nodes end quantum memories. The low phase noise and narrow line-width is crucial to generate high-fidelity repeater links using single-photon entanglement. Different technologies are acceptable if they can be shown to meet the technical requirements. Possible technologies choices might be based on fibre lasers or on diode lasers with extra-long external cavities.

Devices enabling optical spectral multiplexing for Quantum applications (at versatile wavelength - including visible range)
Many wavelengths are addressed in quantum technologies from visible to infrared. Currently, researchers are working with dedicated stabilized lasers. As they will address more and more bandwidth to explore in particular spectral multiplexing, more and more demonstrations will need modulation capacity at various wavelength not covered by off-the-shelf components mainly at 1.5µm and 0.8µm. High-speed, wide-band modulators in the visible range are not available and will remain challenging in the future due to photo-refractive effects. Building "optical arbitrary waveform generators" will probably then rely on high performance components and/or photonic integrated circuits developed for telecom, sensing etc. combined with wavelength conversion architectures and schemes aiming at providing/transferring frequency stability.

Dedicated material synthesis capabilities
Especially for the solid-state material platforms (diamond, silicon carbide, 2D materials, carbon nanotubes, III-V semiconductors, rare-earth ion doped crystals etc.), current commercially available materials are generally not suitable for exploring quantum properties of single or ensemble of defects/impurities. Extremely high crystalline quality (no dislocations, grain boundaries etc.) and a fine tuning of defect incorporation are desired. An additional requirement of such materials is generally a good control over the spin bath environment including the possibility to use specific isotopes in the matrix as well as in the defects themselves. Finally, specific architectures may be needed, including hybrid integration as thin films with different combinations, upscaling to wafer size or combination with designed resonators. This has to rely on specific material synthesis platforms developed or optimized to this end, such as chemical vapour deposition, sputtering, pulsed laser deposition, molecular beam epitaxy, crystal growth etc.

Low loss active devices and connections
To increase the communication distance it is crucial to minimize transmission losses. Therefore, it is crucial to develop fibres and components (such as active switching and modulation devices) with lower propagation and insertion losses.

1.3.B.2 Software challenges

Applications of quantum networks

See 1.3.A.5 for applications.
Many application protocols of a Quantum Internet have already been discovered that highlight the promise of this technology. However, to make full use of Quantum Internet technology it is important to strengthen the development of application protocols that provide value for real world users. Right now, most known applications solve textbook problems, and very little investigation has been done in application protocols for real world use cases – with the exception of QKD. R&D on use cases for a Quantum Internet would bridge the existing gap between what the technology could potentially offer and how potential users could find interesting for their clients.

From a technical perspective, R&D on use cases for a Quantum Internet should go beyond QKD (and more generally, go beyond the prepare and measure stage of quantum network development), and focus primarily on protocols that can be implemented in higher stages of quantum network development, including few qubit quantum processors (quantum memory stage and above). In this, work should address three directions:

1. Use cases for existing application protocols: Here, one takes an existing quantum network application protocol as a given and tries to match it to a real-world use case.

2. New use cases enabled by the development of new application protocols: Here, one tries to identify real world user pain points, and designs and analyses a new quantum network application protocol to realize it.

3. Reducing requirements: Here, one reduces the quantum hardware requirements necessary to implement a specific quantum network application protocol, by a smarter analysis or a new protocol variant (e.g., needing fewer qubits).

A cartography of quantum network applications including the description of the functionality, available protocols, security model and positioning with respect to classical (including post-quantum) techniques (if applicable), desired performance, and an in-depth cost/benefit analysis with available and future technology, can form the basis of this work and lead to a clear roadmap towards real-world use cases. For quantum cryptography applications, in particular QKD, effective integration with PQC algorithms and development of corresponding software toolkits will be crucial for increased resilience.

Programming and controlling quantum networks

The system view of quantum-secure networks is highly relevant to be able to provide the quantum communication service. In order to make a quantum network useful, it is essential to develop a scalable software and network stack, and including a control plane. The purpose of a software stack is to enable arbitrary applications – supported by the underlying hardware system - to be programmed in high-level and platform-independent software. The software stack needed to run quantum network applications differs significantly from the domain of quantum computing, as applications consist, as on classical networks, of separate programs running on different network nodes that communicate only via classical and quantum message passing. This is needed to enable security sensitive applications, like blind quantum computing. While in quantum computing, program execution can proceed by batch processing (send to chip, execute, done), executing a quantum network application requires a continuous integration between the classical and the quantum parts of the execution, for example to react to messages from a remote node. Work on a software stack encompasses many levels ranging from the underlying hardware-software interface, i.e., computer architecture, all the way to high level programming languages. This includes – for example – computer and network architectures suitable for quantum networking, compilers, quantum network operating systems, scheduling algorithms and programming languages. Currently, only a simple system has been developed to execute general quantum network applications.

Next to a software stack, quantum networks can only function provided one can control entanglement generation and provide a resource allocation of network resources to satisfy user demands. In analogy to the classical internet, one can think of a quantum network having a data plane and a control plane. The term data plane thereby refers to the systems that directly manipulate the qubits. The term control refers to the classical signalling needed to direct the data plane to allocate resources for the purpose of generating entanglement in multi-user networks. A quantum network stack is known and demonstrated in small lab size networks that defines a data plane. To scale, a matching control plane is required. Finally, it should allow integration into the operational environments of classical networks.

1.3.C: Objectives and recommendations for quantum communications

→ Objectives, short term (2024 – 2026)

- Improved performance, key rate, and range, for QKD solutions.
- Photonic Integrated Circuits, with efficient and cost-effective experimental devices for quantum communication.
- Deployment of prototype payloads for satellite QKD.
- At least two industrialised QKD systems made in EU and based mostly on a European supply chain.
- Deployment of several metropolitan QKD networks including network orchestration controllers and phase stabilized fibre links between the remote nodes.
- Deployment of large-scale QKD networks with trusted nodes.
- Deployment of CV-QKD, based only on existing telecom components, with reconstruction of the local oscillator at the receiver stage.
- Operation and enhancement of MDI QKD, such as Twin-Field, with a range of 500 km or more, without repeaters or trusted nodes.
- Advances in QKD: testing, certification, accreditation, and availability conditions (e.g., laboratories) to ensure robustness to side-channel attacks at the optical level.
- Development of joint QKD and PQC solutions.
- Demonstrating the use of quantum communication applications for other cryptographic applications, such as private data mixing, secure multiparty computing, long-term secure storage, unforgeable cryptosystems.
- Integration of reliable, small and cheap QRNGs into classical and quantum communication and encryption systems.
- Large-scale entanglement distribution networks outside the laboratory, including network management software.
- Development of Quantum Internet sub-systems such as quantum memories, and processing nodes.
- Demonstration of a functional elementary quantum repeater link over telecom wavelengths and fully independent nodes.
- Design of new application protocols, pilot use cases, software and network stack for a quantum Internet.
- Coexistence of QKD with conventional communications solutions, including multiplexing and switching, allowing one optical channel to be used for multiple services (quantum and classical).
- Built testbeds for Quantum Internet technology to develop, demonstrate and showcase the technology.
- Establishment of standards and metrics defined by Standardisation Developing Organisations (SDOs) for quantum communications.

→ Objectives, medium term (2027 – 2030)

- Cost-effective development, maintenance, and power consumption for QKD systems.
- Scaling of QKD solutions, due to increased market demand.
- Small Form-factor Pluggable QKD transmitter/receiver pair for key distribution.
- QKD systems robust to side-channel attacks, including power consumption and thermal noise, for standalone transmitters and receivers (without physical security).
- Several telecommunications companies selling QKD services with a sustainable business model.
- Deployment of MDI QKD as an industrial product, over very long distances.
- Deployment of European QKD network comprised by a set of federated national QKD networks across Europe.
- Certification of quantum-safe security, including QKD possibly combined with PQC, by at least one national security agency.
- Certification of Small Form-factor Pluggable services and software for universal plug-in.
- Mature quantum communications infrastructure for general usage by organizations and citizens.
- Space-based quantum communications infrastructure.
- Multi-node quantum networks supporting basic quantum Internet applications.
- Deployment of reliable interfaces between qubits at rest and in transit in the network.
- Reliable industry-grade quantum memories to extend communication distances and the demonstration of quantum repeaters.
- Long-distance quantum communication fibre network using quantum repeaters capable of connecting metropolitan areas networks over hundreds of kilometres.
- Demonstration of device-independent quantum key distribution protocols.
- Integration of advanced quantum network applications into classical network infrastructure (i.e. orchestration platform) over a quantum network including quantum repeaters.
- Build test-beds for full stack Quantum Internet technology both to advance R&D, as well as to trial technology with early adopters.

Recommendations

- Complete the deployment of regional, national and Europe-wide QKD networks, with European actors as early customers of European-made QKD systems (e.g., via the EuroQCI initiative), with competitive range, key rate, and performance, integrated with classical networks.
- Integrate QKD and PQC in European cryptographic devices and operational secure networks.
- Design and implement QKD protocols with security based on fewer and fewer assumptions.
- Foster the certification of quantum security by at least one national security agency by 2030.
- Implement test-beds for Quantum Internet technology including metropolitan and national-scale networks with processing nodes, using quantum repeaters.
- Develop industry grade quantum nodes and memories to allow operation in real-world environment and integration in the optical fibre network.
- Develop industry grade control plane, as well as software and network stack for programming and controlling quantum networks linking metropolitan areas, integrated into classical network infrastructure.
- Complete the deployment of regional, national and Europe-wide quantum long-distance networks, with European actors including quantum repeaters and space-based quantum communication infrastructures with dedicated satellites.

1.3.D: EuroQCI

1.3.D.1 Introduction

The European Quantum Communication Infrastructure (EuroQCI) initiative aims to build a secure quantum communication infrastructure that will span the whole EU, including its overseas territories. It was launched in 2019 via the EuroQCI Declaration, signed by all 27 EU Member States in 2019. EuroQCI will be gradually integrated in the IRIS2 (Infrastructure for Resilience, Interconnectivity and Security by Satellite) allowing the quantum distribution of cryptographic keys (QKD). IRIS2 will provide a Union satellite-based, multi-orbital communication infrastructure for governmental use, while integrating and complementing existing and future national and European capacities in the frame of the GOVSATCOM component of the Union Space Programme. EuroQCI will secure critical European assets and infrastructures using first QKD service and, ultimately, offering quantum internet services. EuroQCI spans over terrestrial and space segments. The European Commission coordinates the end-to-end EuroQCI design and deployment, whereas the European Space Agency (ESA) coordinates the design of a space backbone.

EuroQCI design and deployment includes different stages. The first stage included the feasibility evaluation of EuroQCI, the second stage was prepared with in-depth studies on overarching architectures both for terrestrial and space segments. The third stage focuses on the EuroQCI deployment. In January 2023, the national QCI (NatQCI) projects with the aim of deploying national demonstrators of QKD networks by 2025 have started. Those national projects involve relevant academic and industrial stakeholders at each Member State, some of them involve national security authorities. In addition, six for developing main QKD building blocks and to foster the industrial ecosystem were contracted. To support this European effort, the European commission established a Coordination and Support Action, contracting the consortium PETRUS, https://petrus-euroqci.eu/, that integrates partners with a relevant footprint in the design of EuroQCI. PETRUS has the goal to act as a link between all projects, facilitate collaboration, and identify standardisation needs. Further activities involve the development of a testing and certification infrastructure for quantum communication technology in Europe and of cross-border links and optical ground stations under the Connecting Europe Facility initiative. From a current moment's perspective (written in 2023), EuroQCI should reach its operational stage until 2027, following an initial exploration and development phase.

1.3.D.2 Timeline of the EuroQCI initiative

→ Objectives by 2026:

Proof-of-concept of QKD applications in each Member State

- Installation testbeds for quantum communication networks in each member state with the aim to demonstrate QKD applications in real world scenarios. The demonstrations should preferably involve public institutions, who will be the first users of EuroQCI services.
- Educate all stakeholders and raise awareness for QKD technology.
- Planning of the national EuroQCI architecture and network topology including potential cross border links between member states.

Creation of QKD industrial ecosystem in EU-27

- Development of an industrial base for manufacturing of QKD components and systems.
- Establishment of an EU-27 supply chain for QKD.
- Development and adaptation of quantum-ready network components (link encryptors, key management, network controllers) for seamless integration of QKD into existing optical communication networks.

Interconnecting of national EuroQCI networks

- Deployment of cross-border terrestrial QKD links between member states, connecting to the respective national QKD networks.
- Installation of optical ground stations and connections to national terrestrial QKD networks.
- Finalisation of EuroQCI architecture and interfaces for key forwarding between domains (terrestrial/satellite, national QKD domains).

Creation of QKD testing and certification laboratory

- Development of procedures and methodologies for functional and security tests on commercial QKD systems.

Launch of first European QKD satellite

- Launch of ESA's EAGLE-1 mission.
- Functional tests of QKD exchange with satellite and ground stations in member states.

→ Objectives by 2027 - 2030:

Creation of certified QKD market

- Availability of TRL 9 QKD devices from several EU-27 suppliers.
- First fully certified QKD system available.

Initial operation of EuroQCI

- Installation of a quantum communication network covering European cities in several member states.
- Installation of certified QKD systems and network devices.
- Demonstrate QKD secured communication of real data in production network.

Development of operational QKD satellite

- ESA's SAGA (Security And cryptoGrAphic mission) program to develop a satellite-based quantum communication systems with pan-European reach.

1.3.D.3 Overview on current QKD projects of the Digital Europe Programme

The EC launched a number of projects to foster the emergence of a European ecosystem and use of quantum networks based on QKD within the Digital Europe Programme:

- Create a European Industrial Ecosystem for Secure QCI technologies and systems (Industry) dealing with the development of specific equipment (DIGITAL-2021-QCI-01-INDUSTRIAL).
- Deploying advanced national QCI systems and networks (DIGITAL-2021-QCI-02-DEPLOY-NATIONAL) dealing with first deployments of national QCI networks.
- Coordinate the first deployment of national EuroQCI projects and prepare the large-scale QKD testing and certification infrastructure (DIGITAL-2021-QCI-01-EUROQCI-QKD), being responsible to coordinate the developments and findings of the national QCI projects and to prepare for the deployment of a flexible large-scale testing and certification QKD infrastructure.
- A fourth tender on the testing and evaluation infrastructure has been released in July 2023 (CNECT/2023/OP/0032), but at the time of writing no decision has yet been published.

While the first three projects of the Digital Europe Programme are funded grants, the tender for the testing and evaluation infrastructure is a procurement.

As part of the Connecting Europe Facility Programme (CEF), additional funding opportunities with a special focus in cross border connections are announced.

PETRUS, the Coordination and Support Action, is in charge of activities of DIGITAL-2021-QCI-01-EUROQCI-QKD.

1.3.D.4 The road to a fully deployed EuroQCI

To reach a full deployed EuroQCI, there are many dimensions to be taken into consideration. The focus of the current Digital Industrial Projects is to develop quantum technology, and the NatQCIs are conducting initial implementation and testing of QKD technology. However, the fully implementation and operation of the EuroQCI requires that a broad range of topics are addressed. PETRUS adopted the "Five P"-principle model to address these aspects.

The "Five P" principle

The aspects to be considered are based on a 'General Principles of ICT Services', which are principles to evaluate the aspects required to deliver an ICT service. The 5P in the principle stand for People, Processes, Platforms, Provider, and Products.

i. People

People denotes all the aspects relating the people and their relationship with each other (structure, roles, and responsibilities).

The areas that are to be addressed are such as

- EuroQCI Governance: End-to-end governance of the EuroQCI, not only from a technical service perspective, but more from a European Member state perspective, needs to be defined and must manage the rules and regulation to all users of EuroQCI. As EuroQCI will be made up a different QKD services delivered by different Member States, the governance of how each service will be operated and the aspects regarding the service provision among Member States need to be agreed upon.
- Provider Governance: EuroQCI will be delivered by Service Providers and Integrators. As with any other communication service (e.g. mobile roaming) the rules and regulation need to be agreed upon and applied. Its governance must also be negotiated and implemented.
- Education: In order to support EuroQCI and to ensure its continued improvement and maintenance, the right level of skills is required to be available on the market. This requires availability of the relevant education in the academic world as well as the upskilling of the current industrial workforce.

ii. Processes

Appropriate processes need to be defined for all areas of the system under consideration. This especially means that relevant actions and steps are supported by corresponding established processes like for example Service Management, Security, Accreditation, Testing etc. Those processes need to be aligned and agreed across all stakeholders. For each process, a meta process of continuous update and improvement must be in place.

iii. Platforms

Platforms include the main technological ingredients and targets at a defined architecture, agreed interfaces, and an available infrastructure which meets the service levels and operational requirements.

For EuroQCI, all layers of the service must be implemented according to the required service levels, meeting the capacity needs. Additionally, the service must be managed and maintained by appropriate tools, staff, and processes to ensure maintenance of the service. Services should be implemented by appropriate service providers and network operators and integrators across the different NatQCIs.

In order to ensure a fully European wide end-to-end service, interfaces and interoperability rules for EuroQCI needs to be developed and agreed across all member states. Architectural decisions are not only based on technical aspects, but also on regulation and security aspect of each Member State. An example is the implementation of different security levels within EuroQCI, and aspects related to segregation.

Besides that, evaluation laboratories need to be available in order to allow for certification and approval of devices and certification procedures should be put in place to account for the different performance and security aspects of EuroQCI.

iv. Providers

Providers includes integrators, suppliers, and vendors of different levels. Each element of a complex system must be provided for by specialized experts for this area. Providers must be in place to deliver the services or service components, meeting the end-to-end quality and process requirements. Service providers must offer a service portfolio available to meet the end user requirements. Multi service provider agreements must be agreed to deliver interregional services. In order to achieve this each country at a minimum requires to have a service provider in place who is capable to deliver and support QKD services.

Currently there is a lack of a business environment in which providers and integrators have the incentives to develop and implement commercially available QKD services. In order to achieve this, future business opportunities, investment, and sponsorship should be developed.

The industrial EuroQCI projects are working on the implementation of QKD protocols and QKD devices. Note that these projects have providers on their own in terms of required components used in the manufacturing process of their devices. Nevertheless, EuroQCI also requires other providers such as system integrators, network providers or service providers.

v. Products

This P checks, whether supply chains are in place to develop and produce the required products to the required quality and certification, with associated service chains which can be professional and smoothly provisioned and operated according to demand and requirements.

It is required that products are available on the market that meet the required standards and approval. Supply chains need to be implemented to support new installations as well as maintaining existing ones. Ongoing development and improvement of products must be in place to keep up with trends and new requirements or security needs.

The level of maturity of current standards for QKD is low, and in order to ensure a secure and reliable service these standards need to evolve.

The EuroQCI Thematic Working Groups

Following the 7th of June 2023 “Input to Future EuroQCI” meeting and the first meeting of the EuroQCI Working Group (reporting to the GOVSATCOM configuration of the Space Programme Committee) on 20th of June 2023, it was decided to set up 5 EuroQCI Thematic Working Groups (ETWGs), in order to further enhance the progress of EuroQCI.

The ETWGs are established in order to support the development and deployment of the EuroQCI initiative and to provide recommendations to the European Commission thereof. The purpose and objectives of ETWGs are:

- Further develop different aspects to enable the implementation of EuroQCI.
- Provide input in the EuroQCI future steps.
- Provide a forum for Stakeholders to exchange views and share good practice in the development and deployment of EuroQCI.

- Provide recommendations on the development and deployment of the EuroQCI initiative within the Secure Connectivity Programme.
- Support the Commission in the preparation of programmatic and institutional milestones for the EuroQCI initiative.

In accordance with the Regulation (EU) 2023/588 establishing the Union Secure Connectivity Programme for the period 2023-2027, one of the Programme's objectives shall be to 'develop further and gradually integrate EuroQCI into the secure connectivity system' (Art. 3.2 (c)). The EuroQCI is composed of a space infrastructure, a related ground infrastructure, and a terrestrial infrastructure. The ETWG will support and advise the European Commission on all aspects of the EuroQCI, taking into account the views of all of the following Stakeholders:

- EuroQCI Working Group composed of representatives of Member States, who are the owners of the EuroQCI terrestrial infrastructure.
- EuroQCI funded projects funded under the calls DIGITAL-2021-QCI-01-INDUSTRIAL, DIGITAL-2021-QCI-01-DEPLOY-NATIONAL, DIGITAL-2022-QCI-02 and DIGITAL-2021-QCI-01-EUROQCI-QKD of the DIGITAL Programme.
- European Space Agency (ESA).
- EuroQCI Security Working Group, (which reports to the Security configuration of the Space Programme Committee).

The 5 ETWGs and their objectives are as follows:

Roadmap
Develop a roadmap for EuroQCI, covering all aspects (People, Process, Provider, Product, Platform) leading to the full deployment of EuroQCI.

Use Cases
Consolidate all EuroQCI use cases and align on EuroQCI service levels and governance.

QKD Landscape
Provide an overview of the QKD landscape and its relation to other technology globally with a focus on Europe and relevant to EuroQCI. Identify state of the art QKD education, technology and implementations.

Architecture
Define a EuroQCI architecture based on the user requirements.

Interoperability and Standards
Develop approach for interoperability from a cross Member State and from a TerrQCI / SpaceQCI perspective.

1.4

Quantum Sensing & Metrology

1.4.A: Impact, societal challenges and quantum opportunities

Quantum sensing, metrology and quantum imaging are based on exploiting the quantum properties of nature, quantum phenomena, quantum states, their universality and intrinsic reproducibility, the quantization of associated physical quantities or their high sensitivity to environmental changes. Quantum sensors and imagers will provide the most precise, accurate and sensitive measurements in many fields, boosting the performance of consumer devices and services, from medical diagnostics and imaging, high-precision navigation, earth observation and monitoring.

Quantum metrology, with its aspects of validation, certification and traceability, implemented by independent experts, is the prerequisite for a successful transformation of quantum technology into the market.

1.4.A.1 Quantum sensors

The central concept of a sensor is that a probe interacts with a system that carries the property of interest, which then changes the quantum state of the probe. Measurements of the probe may reveal the parameters of this property. Quantum-enhanced sensors either take advantage of the absence of classical noise processes, using a quantum algorithm for extracting the relevant information, or employ probes that are prepared in specifically designed non-classical states. Control over all relevant degrees of freedom and long coherence times enables quantum-limited resolution, even beyond the standard quantum limits (SQL). To achieve this type of control and generate non-classical or even entangled states in noisy real-world scenarios, novel theoretical foundations, tailored materials and experimental techniques are necessary.

Quantum sensing mainly harnesses the quantum properties of simple quantum systems to improve the sensitivity of sensors, render them more robust, and enable them to reach better Size, Weight and Power - Cost (SWaP-C) characteristics. There are many ways to do so: the simplest option is to exploit the system's coherence, i.e. its ability to oscillate between two states reversibly. This translates into an increased interaction time and thus greater sensitivity. Another option is to move beyond the use of a single quantum object (or multiple, unrelated instances of such objects) and instead engineer a many-body quantum state designed to detect the quantity of interest with greater precision, accuracy, bandwidth, or some other figure of merit. This can also be achieved by engineering quantum states (entanglement and squeezing) to overcome conventional noise limits (standard quantum limits). An example is squeezed light interferometry, which increases sensitivity, for instance, in the observation of gravitational waves (GEO600, LIGO) or magnetometry with ensembles of entangled atoms, or sub-shot noise microscopy, or quantum-based super-resolution imaging, and quantum-based target detection and ranging.

A further aim of quantum sensing is to offer new capabilities that classical sensors cannot provide. One example is nanoscale magnetic sensing, enabled by single NV scanning tips (for imaging), or similar single-spin systems. Compared to classical sensors, quantum sensors can also simplify and improve the conditions relating to their use. For example, the measurements of cold-atom gravimeters are based on physical constants, and do not require regular calibration.

There is a wide variety of quantum sensors modalities, including e.g. gas sensors, solid-state sensors, as well as single-atom sensors. All have specific properties that make them suitable for particular applications (e.g. cold atoms for gravimetry and clocks, NV centers in diamond for high spatial-resolution magnetometry). The variety of platforms and applications have very different TRL: some products are already commercially available, while certain platforms are still at an early stage of development. The European industry base for developing quantum sensors is wide, and the Quantum Industrial Consortium (QuIC) contribution through their Strategic Industry Roadmap (SIR) is critical in this chapter.

Solid-state sensors provide stable measurement solutions that are relatively easy to build, integrate, and use due to their spatially confined configurations. They can be operated at room temperature and used to measure a large variety of physical quantities (magnetic and electric field, radio-frequency field, temperature, pressure). Solid-state sensors based on a single spin, such as the NV centers at the end of an Atomic Force Microscopy (AFM) tip, provide nanoscale spatial resolution as well as near-zero perturbation of the device they are measuring. Sensors using a set of spins, e.g. NV centers deposited in a layer close to the surface of the diamond crystal, allow for the parallel measurement provided by optical imaging and, consequently, more rapid measurement than scanning sensors. In addition, their rapid response times permit the instantaneous measurement of time-varying quantities. Moreover, new detection schemes based on the photo-electric detection of the magnetic resonance (PDMR) opens new perspectives for improved performances and integrated sensors.

Atomic gas sensors can reach a very high sensitivity by integrating the signal of a large number of atoms for the cost of a spatially confined implementation. They provide measurements based on physical constants. Being self-referenced and immune to drift over time, they have the added advantage of not requiring recalibration. Products already exist that can operate with little or no human intervention and can function autonomously such as atomic clocks and gravimeters. Spin squeezed and entangled states of macroscopic atomic ensembles of room temperature atoms in a spin protecting environment have been used for magnetometry beyond SQL with potential applications in cardiography and brain tomography. Spin squeezing has been also used to overcome the SQL in Magnetic Induction Tomography (MIT), a method with applications in medical diagnostics and remote sensing. Spin squeezed samples cold atoms have also been produced via cavity-based QND measurements or Rydberg-mediated squeezing is used to overcome the quantum projection noise limit in optical and microwave clocks. The recently reported extension of the coherence time of spin defects in hBN will enable advanced qubit control and sensing using inherently 2D materials.

Optomechanical sensors combine the merits of optical and mechanical sensing in a single device, allowing parallel acquisition of multiple physical signals. Benefiting from the maturity of photonic and MEMS technologies, they are suitable for integration and mass production. The efficient coupling of light with (nano) mechanical motion is currently allowing beating established performances of mechanical (MEMS) sensing in terms of sensitivity and bandwidth in several applications (accelerometry, AFM, mass spectrometry). The use of squeezed light and squeezed mechanical motion, already demonstrated at the academic level, is a next frontier for applications.

Mid- and far-infrared (THz) spectral regions are very interesting to be equipped with non-classical light sources. The spectral regions for $\lambda > 3$ μm are of particular interest both from a fundamental and an applied research point of view. Here it falls in fact the strongest absorptions related to the ro-vibrational transitions of light molecules of environmental/atmospheric and biological interest such as water, carbon dioxide, methane and nitrogen oxides. From a fundamental viewpoint, the study of the absorption spectra with ultrahigh precision and sensitivity can give insights into fundamental laws of physics. From an applied perspective, the high-sensitivity detection of such gases through advanced spectroscopy techniques is important for environmental and health monitoring. These spectral regions would therefore much benefit from the quantum advantage provided by quantum-enhanced sensing techniques.

Superconducting technologies can provide e.g. high-performance single-photon detectors, with near-perfect efficiency, low noise, and ultra-high temporal accuracy that will enable the accurate characterization and development of the quantum networks and quantum computing technologies such as quantum memories, quantum relays, and photonic entanglement sources. Such high-performance detectors will also permit the extension of quantum communication channels through improvements of the Signal to Noise Ratio (SNR) and multiplexing opportunities. In addition, quasi-ideal detector efficiency provides an expanded repertoire of quantum communications schemes with strong technical specifications, such as Device-Independent Quantum Key Distribution (DIQKD) while photon-number-resolving detectors enable extended Quantum Computing schemes based on knowledge of the photonic Fock states used.

A paradigm of measurement in the so-called negative reference frame has enabled measurements of motion and ac magnetic fields not restricted by the Uncertainty Principle. Potential applications range from magnetometry to accelerometry to gravitational wave detection beyond SQL.

Quantum imaging exploits light correlations both to improve the performances of imaging devices toward higher SNR, 3D resolution, and robustness, and to enable completely new imaging modalities (e.g., from ghost to single-pixel imaging and imaging with undetected photons to dual wavelength imaging and correlation plenoptic imaging). Depending on the different approaches and platform, the TRL varies from 2 to 5. No commercial devices are indeed yet available, but the number of patents and the interest from companies are rapidly increasing.

Some of the imaging approaches rely on entanglement in position-momentum, time-frequency, and/or phase-photon number, and bring-in purely quantum advantages: sub-shot-noise microscopy, quantum-based super-resolution imaging, target detection and ranging, imaging with undetected photons. Others, such as ghost imaging and correlation plenoptic imaging, do not strictly require entanglement and can be implemented by highly tunable, cost- and resource-effective low-coherence sources, such as thermal and chaotic light; potentially, passive illumination from the Sun, stars, and available environmental light can suffice. This approach, combined with the availability of ultra-fast high-resolution sensors such as SPAD arrays, opens up the possibility to develop ultra-fast quantum imaging devices for demanding applications such as studying neuronal activity, detecting and ranging rapidly moving targets, in real time, quantum-enhanced autonomous drive, 3D x-ray imaging. SPADs can be fabricated using state-of-the-art semiconductor technology, but to enable these quantum imaging applications, SPAD array development is needed.

1.4.A.2 Quantum metrology

Quantum metrology devices, including sensors and measurement standards, are the basis of the definition and dissemination of the International System of units (SI). They provide universal and highly reproducible references for the physical constants defining the SI: the velocity of light, the Planck Constant, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, the elementary charge, based on quantum phenomena (quantization of atomic energy levels (time and frequency), quantum Hall effect (electrical resistance), Josephson effect (electrical voltage), universality of elementary charge (electrical current) are all defined by quantum standards.

Prominent examples of these universal and highly reproducible quantum metrology devices are cold-atom clocks, quantum electrical standards based on solid-state quantum phenomena, such as Josephson effect, quantum Hall effect and associated quantum instrumentation (Superconducting Quantum Interference Device, Josephson programmable voltage standards (JPVS), Josephson arbitrary waveform synthesizer (JAWS)). The new definition of the SI system in terms of physical constants allows, in principle, the realization of the units by anybody, anywhere, and any time, also directly in applications. As a prominent example, Global Navigation Satellite Systems (GNSS) utilize atomic clocks in satellites instead of calibrated classical clocks. Improving the practical fidelity of quantum metrology devices, such as scalability, can advance direct applications of quantum metrology. For example, enabling quantized signal generation and detection in practical applications may widen the industrial impact of the SI in cryogenic quantum technologies. Overall, the development of quantum technologies enables facilitated systems for user-friendly and economic metrology standards that can be operated in user-friendly and economic cryo-systems.

The development of quantum technologies is accelerating, offering huge opportunities and challenges for generating new industrial products and services. Inevitably, the demand for metrology and metrological services is growing in tandem and is entering a new era. Innovation and investment in metrological capability and dissemination are essential to match this trend. National metrology institutes in Europe must cooperate to achieve this. EURAMET provides an excellent framework and a vehicle for such cooperation, through the establishment of dedicated metrology research programs, and of the European Metrology Network for Quantum Technologies (EMN-Q). The EMN-Q will analyze European and global metrology needs and address these in a coordinated manner developing common metrology strategies including aspects such as research, infrastructure, knowledge transfer and services, see the EMN-Q Strategic Research Agenda[1] . This SRA is based on the mission of the EMN-Q “to support competitiveness and innovation of the emerging European Quantum Industry by metrology science, services, and knowledge transfer[2] .

1.4.A.3 Industrialization and enabling technologies

From an industrial perspective, it is necessary to consider not only the technical performance, but also the practical aspects of sensing solutions (e.g. size, weight, power, reliability, performance in challenging environments such as mobile or flying platforms with vibrations, noise and temperature variations, and cosmic radiation). For example, the Chip-Scale Atomic Clock, although underperforming a conventional atomic clock, has more potential applications in the short term due to its ease of integration, low weight, compact form factor, and lower cost than the standard atomic clock systems. Another example is cold atoms on chip combined with integrated photonics that will allow decreasing the size of cold atom sensors by two orders of magnitude as compared to existing laboratory demonstrations. Many quantum techniques offer interesting possibilities for building compact, robust, reliable, integrated sensors at room temperature, that have long-term stability.

For industrial applications, many enabling technologies are needed in addition to the quantum sensing platform itself. These enabling technologies make it possible to integrate the quantum sensor in a module or system - a

[1] : European Metrology Network on Quantum Technologies: Strategic Research Agenda, Draft version, https://www.euramet.org/european-metrology-networks/quantum-technologies/strategy/strategic-research-agenda
[2] : **https://www.euramet.org/european-metrology-networks/quantum-technologies**

self-standing product – that can be utilized in the application environment. As an example, cold atom gravimeters are, thanks to in-depth development on the lasers, vacuum system and control electronics, already compliant with operation at geophysical sites out in the field. These enabling technologies include e.g. integrated photonics, laser sources, single photon detectors, cryogenics, cryogenic CMOS technologies, as well as high-speed and RF electronics in room temperature. These are covered in more detail in the *Enabling technologies* chapter of this SRIA. We point out here some specific needs that sensors pose for enabling technologies.

Advanced lasers and photonic circuits mostly support the development of cold-atom/ion-based quantum technologies. Advanced photon counters and non-classical light sources are key for developing and implementing fiber- and space-based quantum communications, Linear Optical Quantum Computing, and quantum imaging, and optical clocks. In metrology and sensing applications, the stability of the lasers is of utmost importance.

Recent years have shown that also cryogenic technologies have significant industrial potential. The energy-efficiency and size are aspects of scalability due to the large energy overheads related to refrigerating the devices and technologies into low temperatures. These aspects can be assessed, e.g., by developing supporting cryogenic electronics such as CMOS or by the optical control of cryogenic quantum electrical devices, or solid-state cooling technologies to enable miniaturized cryogenic coolers from communication and computation to sensing applications.

Quantum sensing and metrology may also be used as enabling technologies for other quantum technologies. Such potential does not depend only on the technical merits of the measurement, such as accuracy or sensitivity, but also on more practical aspects such as user-friendliness, scalability, and energy-efficiency.

One example is using single-photon detectors as part of a quantum communication system or as part of a (photonic) quantum computer. Another is the control of single-electrons on quantum level as enabling technology both for metrology and for solid state qubit-platforms. Further, e.g. a scanning NV microscope can be used for analyzing quantum materials including superconductors and quantum magnets, targeted at the QC industry and research activities.

1.4.A.4 Applications of quantum sensors

i. Use cases in biology

Several use cases concern biological applications such as the detection of metabolic activity and the identification of specific metabolites in less than 100 living cells (and in some cases at the level of a single cell), or nuclear spin detection and the characterization of molecules in volumes of a few femtoliters using NV-center techniques. Other use cases include remote assessment of heart disease in clinical applications or deep tissue optical imaging based on high-etendue optically pumped ultra-narrowband frequency filters. Of their side, opto-nanomechanical devices are now capable to detect and analyse the vibrations of a single bacterium, or to weigh an individual virus.
Coherently controlled spin systems can be used as a resource for ultra-sensitive Magnetic Resonance Imaging (MRI). Hyperpolarized/metabolic MRI is an innovative imaging technique that has significant implications for medical diagnostics and research. By leveraging hyperpolarization, this method enables enhanced visualization of metabolic processes within the body. Similar to quantum sensors used in quantum information analysis, hyperpolarized/metabolic MRI serves as a valuable tool for investigating complex biochemical pathways and metabolic activities.

This technology provides unprecedented insights into cellular metabolism, allowing researchers to study diseases at a molecular level and potentially detect early-stage abnormalities. With its high spatial resolution and non-destructive characteristics, hyperpolarized/metabolic MRI has the potential to revolutionize various fields, including oncology, neurology, and cardiology. It can be employed to track subtle fluctuations in metabolic activity and assess the effectiveness of therapeutic interventions, opening new possibilities for personalized medicine and advanced treatment strategies. Through the integration of hyperpolarization and metabolic imaging, this MRI technique offers a scientific approach to enhance healthcare and deepen our understanding of the intricate workings of the human body.

Optically pumped magnetometers (OPMs), which use high-density atomic ensembles and optical readout of spin precession, have reached sub-femtotesla sensitivity, suitable to detect magnetic signals generated by human brain on-scalp. In fact, OPMs are currently used in biomedical applications such as magnetoencephalography (MEG), magnetocardiography (MCG) and magnetomyography (MMG). Since OPMs do not need cryogenic cooling apparatus, many research projects and private companies are competing to develop whole-head helmets with arrays of OPMs for practical and cost-effective functional neuroimaging. Improvements in scalability and functionality of OPMs-based MEG would greatly improve the spatial as well as temporal resolution in the diagnosis of neurological disabilities and disorders. Finally, MEG in Earth's unshielded environment has been demonstrated using an optical magnetic gradiometer.

ii. Sensing and testing

In RF sensing, the analysis of the electromagnetic spectrum and detection of transient signals based on NV centers or Rydberg atoms in vapour cells is being studied. These technologies could offer high broadband sensitivity and polarization detection capabilities. These could allow RF spectrum monitoring for instantaneous reallocation of communications frequency bands (cognitive radio) and for future 5G deployment. RF magnetometry with squeezed and entangled states of macroscopic room temperature atomic ensembles in spin protected cells has demonstrated realistic potential in medical applications. Also, ultra-wideband RF detection in a compact form factor is studied using superconducting Josephson-based antennas that can provide smaller and form factor and wider bandwidth, allowing new opportunities for their integration.

Object detection and ranging, for classical Light-based Detection And Ranging (LiDAR) and RADAR applications based on high-performance atomic clocks and photonic detection systems can be improved using single-photon detectors. In the long term, the use of entanglement and quantum-correlation could enable a quantum RADAR or quantum LiDAR system that is theoretically more sensitive and robust against spoofing. Current experimental limitations relating mainly to suitable sources and detection schemes suggest medium-term applications for close-range surveillance. For LiDAR, using the rapid response of current photonic detection systems (e.g. SPADs and SNSPDs), time-of-flight measurements can be resolved at centimetre scales, with further precision possible using interferometric sensing techniques.

Other all-optical system exploiting tailored quantum states (e.g. entangled states, single-photon states and non-classical correlation) enable perspectives of practical application in the field of super-sensitivity (achievable exploiting sub-shot-noise solutions) super-resolution microscopy, and non-linear interferometry.

Non-destructive testing of magnetic materials and generally in materials science are being developed with single NV scanning tips with high spatial resolution or with sets of NV centers with parallel measurement. Example use cases are the characterization of small currents to control microelectronic circuits for the semiconductor industry or automated test equipment based on integrated NV sensors.

High-performance single-photon detectors, with near-perfect efficiency, low noise, and ultra-high temporal accuracy will enable the accurate characterization and development of the quantum Internet and QC technologies such as quantum memories, quantum relays, and photonic entanglement sources. Such high-performance detectors will also permit the extension of quantum communication channels through improvements to SNR and multiplexing opportunities. In addition, quasi-ideal detector efficiency provides an expanded repertoire of quantum communications schemes with strong technical specifications, such as device-independent QKD, while photon-number-resolving detectors enable extended QC schemes based on knowledge of the photonic Fock states used.

Josephson Arbitrary Waveform Synthesizers (JAWS) allow to produce quantum-accurate arbitrary waveform signals with a good internal energy-efficiency. However, the conventional method of using a wide-bandwidth coaxial cable to bring the necessary current pulse drive signals into the device is problematic due to thermal load issues. Better driving methods are needed to enable any wide use of such technology. There is also a growing need for the measurement of microwave frequencies in cryogenic environments. As examples, qubit-based quantum sensing may allow quantum-accurate microwave power measurements, and optical pulses can be used for sampling oscilloscopes for electrical signals with a bandwidth approaching THz in cryogenic temperatures.

iii. Gravity and seismology

The development of unmanned ground-based mobile gradiometers will make possible land-based gravity surveys, e.g. for the detection of underground infrastructure or cavities; exploration of natural resources, or for use in in civil engineering, archaeology, geodesy, volcanology and hydrology will become possible with the development of unmanned ground-based mobile gravimeters and gradiometers. They will come as a complement to static infrastructures based on one or more instruments.

Airborne and seaborne gravimeters will enable geological-tectonic mapping, geodetic surveys, oceanography, and deposit exploration and improvement of Inertial Navigation Systems. Sea-floor gravimeters will facilitate marine gravity surveys, reservoir management, and deposit exploration. Space-borne quantum gravity missions will improve the resolution of previous measurements using classical technologies. Cold atom sensors are also seen as promising candidates for tests of fundamental physics in space (for example Einstein's Equivalence Principle).

Ground motion sensing for seismology, earthquake engineering and geodesy will also be made possible by transportable optical clocks, inertial sensors with atomic interferometry, and high-performance frequency transfer of optical references. Here, atomic clocks and atomic interferometers can provide complementary measurements of potential differences on larger scales and local gradients, contributing to improved Earth and climate monitoring, such as melting of ice shields and monitoring of water storage. More, space accelerometers based on atom interferometry will improve the measurement of the non-inertial accelerations experienced by satellites dedicated to the gravity mapping of the Earth, leading to improved determination of the Earth gravity field, and its spatial and temporal variations, at the global and regional scales. The deployment of quantum sensors at all scales will improve Earth and climate monitoring, such as changes in the ocean circulation, melting of ice shields and monitoring of water storage.

iv. Positioning, navigation and timing

There are a large number of use cases for high-precision atomic clocks. High-stability cold-atom microwave clocks have many applications in time and frequency metrology, timescale generation, and synchronization. Current trends focus on optimizing robustness and SWaP-C to promote mobile or long-life applications and operations in demanding environmental conditions (e.g. aerospace), as well as increasing the fundamental frequency of the optical domain for higher performance. For the latter, a frequency comb allows optical frequencies to be translated into RF signals, if relevant to the user.

In the field of positioning, high-precision atomic clocks have several applications. Terrestrial navigation is enabled by distributing timing signals with sub-ns accuracy, enabling position determination to within centimetres, which is highly desirable for self-driving cars. An atomic clock on board a moving vehicle (e.g. boats, drones, airplanes, or satellites) would be able to detect spoofed GNSS signals based on their mismatched timestamps. Knowing that the GNSS signals are compromised, the vehicle could switch to alternative navigation modes, e.g. inertial navigation. Optical clocks on board GNSS satellites would allow the waiting time between synchronizations with ground clocks to be increased and would improve the accuracy of the navigation signals.

Atom accelerometers and gyroscopes with improved long-term stabilities with respect to their classical counterparts will be integrated into quantum inertial measurement units, and eventually hybridized with classical sensors, allowing for reducing positioning errors. Navigation will also profit from the gravity maps obtained by gravity quantum sensors, allowing for a better separation between the vertical acceleration of the carrier and the gravity acceleration and for improved relocation in terrain-aided navigation. 3D measurement of the position and orientation of objects in indoor and outdoor applications with a fully-integrated CMOS sensor will be enabled by NV centers magnetometry. New methods of geodesy will also be made possible by transportable optical clocks, inertial sensors with atomic interferometry, and high-performance frequency transfer of optical references. Here, atomic clocks and atomic interferometers can provide complementary measurements of potential differences on larger scales and local gradients. Determining the position and orientation of self-driving vehicles will be enabled by atomic vapor cells. Cold atom accelerometers and gyroscopes also have very high accuracy, and will increase the performance of high-end Inertial Navigation Systems (INS) for autonomous navigation. Navigation based on maps of the earth magnetic field will be made possible by high sensitivity NV centers in diamond magnetometers.

Many metrology use cases, such as chronometric levelling (relativistic geodesy), the connection of height reference systems on the European scale, and the exploitation of fiber networks for time and frequency dissemination are possible through the development of high-performance and transportable optical clocks. Optical clocks can provide stable optical frequency references that enable increased data transfer density in fiber networks and may play a key role in the synchronization and phase stabilization of future quantum networks. The availability of accurate timestamps at each network node would render telecommunications or power grid networks less vulnerable to GNSS disruptions. GNSS signals are currently important for synchronizing such networks, however they are vulnerable to jamming and spoofing.

v. Traceability of measurements

It is necessary to develop a measurement and testing ecosystem able to provide traceable measurement, characterization, and evaluation of quantum devices and technology as a service to European industry, SMEs, RTOs and academia, exploiting the traceability metrology chains when available, and, eventually extending the traceability into the regime of interest for the quantum technologies, when they are not available, e.g. extend radiometric traceability to the single-photon regime, develop specific quantum resource quantifiers and the related standardized measurements for their estimations. The national metrology institutes are the natural actors in this field.

1.4.B: Scientific, Technological and Industrial challenges

1.4.B.1 Physical platforms

Because of the wide range of applications and their specificity, a broad range of physical platforms needs to be considered. In this chapter we will introduce several physical platforms used having potential in sensing applications including their inherent advantages and drawbacks. The following also considers the platform specific development challenges and ambitions.

Trapped ions

- **Advantages**
  Single/few ions exhibit high accuracy due to resilience against environmental perturbations.

- **Drawbacks:**
  Limited signal to noise ratio results in long integration times.
  Relatively large sensor size.

- **Typical sensor/application:**
  Optical clock, magnetic and electric field sensor.

- **Development challenges and ambitions in the short term (2024-2026) and medium term (2027-2030)**
  Short term: Demonstrate each of the following individually: miniaturize vacuum system, ion traps; integrate electronics and optics into trap chip; scale-up number of ions.
  Long term: Fully integrated and miniaturized many-ion trap system with integrated electronics and photonic structures on chip.

Ultra-cold atoms

- **Advantages:**
  Easily provide large ensembles of atoms (tens of thousands to tens of millions) of atoms, increasing signal-to-noise and significantly reducing time needed to average to desired precision.
  Large atom population increase sensitivity/signal to noise ratio. Using atom chips combined with integrated photonics allows miniaturizing the size of the sensors.
  Intrinsic high accuracy and long-term stability, with the possibility of tying the measurement to fundamental constants and avoiding the need for calibration.

- **Drawbacks:**
  Relatively large sensor size, in particular optical atomic clocks. Microwave clocks and gravimeters are on the market and <1m3. Transportable optical atomic clock prototypes of a few m3 volume have been built.

- **Typical sensor/application:**

Gravimetry and gradiometry: geophysics, geodesy, hydrology, volcano monitoring, carbon sequestration, reservoir monitoring, detection of buried structures, subsidence monitoring, navigation.
Gyroscopes, and accelerometers: high precision inertial navigation, tests of fundamental physics
Atomic clocks: GNSS, PNT, VLBI, geodesy (chronometric levelling).
Magnetic field sensors: navigation.

- **Development challenges and ambitions in the short term (2024-2026) and medium term (2027-2030)**
  Short term: Demonstrate continuous super radiant clock.
  Short term: Reduce optical clock size by factor of two relative to currently smallest size in Europe.
  Short term: Integrate quantum accelerometers in inertial measurement units and demonstrate improved inertial navigation.
  Short term: Build a space accelerometer demonstrator.
  Short term: Develop strapdown gravimeters for on-board applications.
  Short term: Develop ruggedized high stability gradiometers for field applications.
  Short term: Demonstration trapped/guided quantum accelerometry and gyroscopy on atom chips.
  Medium term: Laser system miniaturization, e.g. laser sources, optical benches, photonic chips, fiber-based solutions, miniature optical frequency combs, optical reference oscillator.
  Medium term: Physics package miniaturization and electronics integration to allow better performance for given SWAP-C.
  Medium term (2027-2030): Connecting quantum sensors into networks, e.g. time and frequency distribution networks for optical clocks (for geodesy, network synchronization, fundamental science), comparison of data from gravimeters for underground exploration.
  Medium term: Overcoming limitations of current sensors: understanding and overcoming effects that limit coherence or induce systematic shifts (black body radiation, collisional shifts,...); enabling averaging proportional to 1/atom number (e.g. exploiting entanglement) and 1/averaging time (e.g. continuous phase-coherent measurement), instead of the usual 1/sqrt(atom number) and 1/sqrt(time); enabling the use of larger atomic ensembles without performance degradation; improving short-term stability (e.g. better reference resonators for optical clocks).

Warm and hot atomic vapors

- **Advantages:**
  System easy to miniaturize.
  Large atom or ion population increase sensitivity/signal to noise ratio.

- **Drawbacks:**
  Reduced accuracy due to atom-atom interactions and thermal motion in some applications

- **Typical sensor/application:**
  Gyroscope, atomic clock.
  Magnetometry, magnetic induction tomography.
  Hybrid sensors using entanglement of optomechanics and atomic spins.

- **Development challenges and ambitions in the short term (2024-2026) and medium term (2027-2030)**
  Short term: Miniaturization of the cell and control and measurement system.
  Short term: Improvement of reproducibility and durability of gas cells, and wafer level manufacturing.
  Short term: Availability of lasers with sufficient integration and power and quality.
  Short term: Development of vacuum packaging, development anti-reflection and anti-relaxation coatings.
  Medium term: Special requirements for space and other harsh environments.

Nano- and micro-mechanical oscillators and opto-mechanical systems

- **Advantages:**
  Versatile systems that detect mass, acceleration and force, and through proper functionalization also electromagnetic fields, charge and spin.
  All key parameters are defined by geometry, which can be engineered through (nano-/micro) fabrication. For example, frequencies from mHz to GHz, masses from picogram to kilogram.
  Very long coherence times in excess of 100 ms.
  Compact, installation at point of interest.

- **Drawbacks:**
  Subject to thermal noise which needs to be removed by cryogenic and/or laser cooling for the most sensitive applications.
  Typically require high vacuum, or mitigation required if operating in air and liquid.

- **Typical sensor/application:**
  Ultra-sensitive and fast force microscopy, including nano-scale MRI by means of magnetic resonance force microscopy.
  Quantum-calibrated thermometry also for metrology.
  Measurement of nanoscale soft matter and biological objects.
  Quantum (random access) memory.
  Quantum transduction from the microwave (superconducting qubits) to the optical domain (for transport on optical fiber).
  Accelerometers.

- **Development challenges and ambitions in short term (2024-2026) and medium term (2027-2030)**
  Short term: Reduce reliance on cryogenic cooling by further improvement of coherence; develop functionalization that increase coupling to sensor; develop compact, quantum-noise limited readout modalities (optical/microwave sources).
  Short term: Study of the systematic effects, reduction of the self-heating by the interrogation laser light, improvement of the system “fiber + resonator” assembly (glued or welded) for better reproducibility.
  Medium term: Miniaturization and integration with quantum-noise limited readout; sensitivity beyond the standard quantum limit; vacuum packaging.
  Medium term: Development of the compact detection and signal treatment systems (electronics, FPGA); development of the system for packaging system for the sensor for industrial environment.
  Medium term: Further development of measurements beyond SQL using negative mass reference frame approach.

Superconducting nano-circuits

- **Advantages:**
  Versatile technology.
  Provide improved, facilitated, versatile, user-friendly, and cost-efficient quantum electrical standards, instrumentation, and measurement bridges.
  Enabling technology to other modalities.

- **Drawbacks:**
  Operation requires cryogenic conditions (liquid helium, 4 K) except for high-Tc superconductor-based applications (70 K, compact and portable cryogenic machine).
  Fabrication requires sophisticated material and thin-film technology.

- **Typical metrology sensor/applications application:**
  SQUID magnetometers, SNSPD single-photon sensors, photon-number resolving sensors, microwave sensors.
  Primary quantum voltage standards for dc and ac metrology up to the low MHz frequency regime at the 10-volt level, including applications in electric power metrology.
  JAWS-based digitally enhanced and fully digital measurement bridges for multipurpose ac metrology.
  Quantum voltage small-signal and noise generators for primary noise measurements and resistance thermometry, and for the calibration of detectors and signal analyzers.
  Quantum voltage measurement systems for metrology of non-electrical quantities like temperature (Johnson noise and resistance thermometry) or mass, for example in 'Kibble' balances for fundamental mass metrology.
  Instrumentation and methods based on QND schemes for quantum information, computation, and communication, overcoming noise limits and reducing the invasiveness of measurements: e.g., superconducting noise-suppressed amplifiers for the readout of qubits and entangled microwave photons implemented by parametric amplifiers.

- **Development challenges and ambitions in short term (2024-2026) and medium term (2027-2030)**
  Short term: Improvements of SNSPDs or other single-photon detectors: large arrays, integration with integrated optics, improved detection bandwidth, from single-photon detection to photon number resolving sensors, scalable readout circuits, energy-efficient readout circuits (e.g., optical readout to replace semiconducting amplifiers and electrical cables).
  Short term: creation of a superconducting foundry for increased-maturity fabrication.
  Short term: Reduction of size and energy consumption of the cryostats (e.g. with dedicated design made on purpose) [short term], new materials operating at higher critical temperature, and solid-state coolers [medium term].
  Short term: Implementation of multi-purpose, cost-efficient JAWS systems driven with optically generated pulse patterns, enabling improved performance with respect to increased signal amplitude and/or frequency.
  Short term: On-chip integration of opto-electronic components.
  Medium term: Energy-efficient cryogenic technologies that do not conduct too much heat into cryostat nor dissipate too much in the cryogenic volume. This work can involve, e.g., optical communication between room temperature and cryogenics, since optical fibers have a wide bandwidth and negligible heat conduction. This requires also development of energy-efficient optoelectronic converters, cryogenic integrated photonics, and cryogenic signal generation. techniques such as JAWS and SFQ.

NV centers in diamond and other impurities/defects in solid state, such as rare earth ions in solid state and spin defects in solid-state

- **Advantages:**
  System easy to miniaturize.
  Atomic scale spatial resolution achievable.
  Operation at room temperature and no need of vacuum for NV center applications.
  Possibility of optical detection or photo-electric detection of the magnetic resonance.

- **Drawbacks:**
  Cryogenics for rare earth defect applications.
  Availability and synthesis as highly pure and well controlled materials

- **Typical sensor/application:**
  Nano-scale imaging of magnetic field.
  Wide-field imaging with optical diffraction spatial resolution.
  Deep tissue optical imaging e.g. of oxygenation in connection with stroke, myocardial infarction or sports medicine. Alternatively for non-invasive optical tumor biopsy or other applications.
  Radio-frequency (RF) spectrum analysis.
  Gyroscopes with expected performance/cost between MEMS and high end optical gyros.

- **Development challenges and ambitions in short term (2024-2026) and medium term (2027-2030)**
  Short term: Improve the technological control of the doped crystal: quantum grade material, higher defect concentration (while preserving quantum coherence), preferential orientation, deterministic implantation.
  Short term: Explore new detection schemes (electrical) and compare them with established techniques (optical). Exploring new host material dopant combinations, decreasing homogeneous bandwidths, reducing spin-flip rates. Exploring embedded nano-diamond crystals.
  Medium term: Keep on improving the material, realize registers of NV and C13 to enhance the interrogation time thanks to a quantum memory. Generalize the use of entanglement to achieve measurements below SQL. Developing and testing demonstrators, clinical studies.

Two-dimensional electron gas semiconductor circuits:

- **Advantages:**
  Small device size.
  Fabrication technologies can be derived from and advanced with state-of-the-art semiconductor microelectronics technology.

- **Drawbacks:**
  Operation requires cryogenic conditions (liquid helium, 4 K).

- **Typical sensor/application:**
  Quantum Hall-based primary resistance standards for routine calibration applications in the dc and ac regimes.

Quantum resistance measurement systems for metrology of non-electrical quantities like mass, for example in ‘Kibble’ balances for fundamental mass metrology.

- **Development challenges and ambitions in short term (2024-2026) and medium term (2027-2030)**
  Short term: Improve maturity for sensing applications through integration and demonstrations of sensing proof-of-principle.
  Short term: Implementation of advanced, robust, and stable quantum Hall devices made from novel materials like topological insulators (van-der-Waals heterostructures) or novel organic and metal-organic molecular frameworks.
  Short term: Implementation of advanced user-friendly and economic high-precision resistance bridges based on the concept of the cryogenic current comparator.
  Medium term: Improve quality, reliability of production and stability of 2-DEG materials like GaAs- heterostructures and silicon based (SiGe/strained Ge) two-dimensional electron/hole gas (doped and undoped structures) for enhanced electron quantum level control.

Charge devices and quantum dots

- **Advantages:**
  Small device size.
  Current and charge metrology; Clocked transport of single charge carriers for the realization of future primary current standards, also enabling fundamental consistency tests in electrical quantum metrology.
  Enable the implementation of single-electron quantum optics and interferometers, for emerging QT in various fields like quantum information, communication and quantum computing and sensing.

- **Drawbacks:**
  Overall maturity for sensors low.
  Operation requires cryogenic conditions in the sub-kelvin range.

- **Typical sensor/application:**
  RF detection, quantum radar.
  Clocked transport of single charge carriers for the realization of future primary current standards, also enabling fundamental consistency tests in electrical quantum metrology.
  Enable the implementation of single-electron quantum optics and interferometers, for emerging QT in various fields like quantum information, communication and quantum computing and sensing.
  Current and charge metrology as well as electrical metrology for and with electron wave packets, including local time-resolved electro-magnetic sensing with ultra-short electrical pulses, flying electron tomography and metrology for semiconductor technology platforms for quantum computing/simulation/communication.

- **Development challenges and ambitions in short term (2024-2026) and medium term (2027-2030)**
  Short term: Improve maturity for sensing applications through integration and demonstrations of sensing proof-of-principle.
  Short term: Upscaling of single-electron currents (higher count of quantum dots), requires solutions similar to the upscaling problem for solid state qubits.
  Short term: Development of highly efficient and coherent single electron sources and single-shot single electron detectors for localized and propagation electrons.
  Short term: Development of ultrafast quantum control for electron quantum states.

Medium term: Transfer of device fabrication from academic clean room facilities to more industrial like facilities to increase device quality and reproducibility.
Medium term: Assess and develop technology platforms for state preparation and manipulation of electronic quantum states with high purity and fidelity for ballistic electron sensors and flying qubits.
Medium term: Integration with semiconductor device technology used for semiconductor qubits.
Medium term: Implementation of robust and user-friendly devices and systems.

Nonclassical states of light

- **Advantages:**
  Fast and cost-effective solution typically operated at room-temperature.
  Promising for short term application.
  Possibility to investigate the response of a physical system (from the point of view of the sources/detectors) by measuring photons in other regions of the spectrum.

- **Drawbacks:**
  Typically, prone to losses
  Source quality, i.e., brightness, purity and fidelity need to be improved.

- **Typical sensor/application:**
  Sub-shot noise microscopy for photo-sensitive samples.
  LIDAR application for mid-range sensing and imaging.
  Super-resolution fluorescence microscopy.
  Quantum Bio-sensing and imaging.

- **Development challenges and ambitions in short term (2024-2026) and medium term (2027-2030)**
  Short-term: Tailoring specific properties of the quantum light source (e.g. brightness, spatio-temporal modal structure, ...).
  Short-term: Improving the performances of single-photon detectors with spatial resolution (e.g. overall efficiency, temporal resolution, ...).
  Short-term: Identify situation and design practical solutions where the detection of effect at non-easily accessible region (e.g. far-IR or THz) of the spectrum can be done by measuring photon in the visible near-IR region.
  Short-term: Demonstration of mid- and far-ir sources of non-classical states of light .
  Medium term: Translate the results achieved in the visible near-IR to the X-ray domain where the reduction of the radiation dose is of utmost importance
  Medium term: Coupling the all-optical solutions with other platforms in order to combine quantum technologies to further improve the performances of the different platforms.
  Medium term: Quantum enhanced ro-vibrational molecular spectroscopy.

1.4.B.2 Ambitions common to all modalities

To achieve the central goal of "demonstration quantum sensing beyond classical capabilities for real-world applications" the following central challenges need to be addressed:

- Develop techniques to achieve full control over all relevant quantum degrees of freedom and to protect them from environmental noise and malicious interventions.
- Identify correlated quantum states that outperform uncorrelated systems in a noisy environment and methods to prepare them reliably.
- Leverage interdisciplinary expertise and join forces with other fields, such as the signal processing community to further advance the limits of sensors sensitivity and resolution and to implement the best control protocols, statistical techniques (e.g. Bayesian) and machine learning algorithms for sensors specific signal processing and algorithms.
- Packaging and miniaturization of quantum systems, together with the supporting systems, which requires significant developments in the enabling technologies, including cryogenics, photonics and semiconductor technologies.

1.4.B.3 Challenges and ambitions related to Metrology

The actual and forthcoming quantum devices are based on very specific components and modules. Their development requires devices that require an iterative sequence of steps, composed by Design, Build and Measure. Once a quantum device has been fabricated, its characterization and testing provide the necessary insights to improve its design, until a first minimum viable and validated product is realized. Inevitably, the demand for metrology, testing and characterization services will grow in tandem because of the raising of the quantum technologies market.

The challenge is to develop a network of testing and characterization labs with globally unique equipment and competencies, that will be the infrastructures offering traceable testing and validation services. This will also require a further metrological effort to develop improved metrological standards and traceability chains to support the standardization and validation of the quantum devices and subsystem arriving in the market.

Based on the extensive liaisons with stakeholders, the following metrology topics are of highest importance for the development of the necessary metrological needs to support European quantum technology industry in a sufficient manner:

- Metrological support for quantum technologies, e.g., for example testing, standards, measurement technologies, and device characterization.
- Metrology for evaluating the security of quantum communications – addressing fiber and satellite QKD, and advanced protocols that could lead to a quantum internet[3] .
- Testing, validation, and calibration of the developed photonic devices (including QPICs – quantum photonic integrated circuits), 2D materials and systems, and quantum-enhanced sensors.
- Pre-normative research on metrology of quantum computing systems components with a focus on testing, validation and future measurement services.
- Infrastructures to extend and accelerate applications and services based on quantum sensors, in particular high-quality time and frequency dissemination via optical links (fiber networks & free space links).

[3] e.g., see European Commission Report "Current Standardisation Landscape and existing Gaps in QKD" figure 1 and the final paragraph in section 4.2

1.4.C: Objectives and recommendations for Sensing and Metrology

→ Objectives by 2023 - 2026:

- Establishment of a reliable, efficient supply chain including materials, fabrication facilities, enabling technologies, quantum devices and sub-systems for quantum sensors.
- Creation and utilization of pilot lines for improved access of companies and researchers to quantum platforms that are useful to develop quantum sensors.
- Engineering of materials using nanofabrication, such as topological and 'Dirac cone' materials and systems; synthesis of ultra-pure materials (e.g. diamond, SiC), doped nanoparticles, color centres.
- Development of sensors and measurements services at single-photon and entangled-photon level and the relative traceability chains for optical quantum technologies ranging from quantum communication to quantum sensors to (optical) quantum computing.
- Establishment of standardization, calibration and traceability (in a metrological sense) for new sensor technologies and prototypes of compact electrical quantum standards with enlarged application ranges.
- Prototypes of quantum sensors, for example transportable optical clocks and their comparison over large distances, onboard atomic gravimeter, accelerometer and gyroscopes, transportable electric, magnetic, radio-frequency field, temperature and pressure sensors, table-top prototypes of quantum-enhanced, super-resolved, and/or sub-shot noise microscopy, spectroscopy, and interferometry, as well as quantum LIDAR.
- Theoretical modelling of real-world noise scenarios and the identification of noise-immune quantum states and algorithms: employing machine-learning algorithms, Bayesian inference and quantum error correction for sensing.
- Development of key enabling technologies, such as photonic integrated chips (PIC), low-noise and RF electronics, miniaturized lasers, traps, atom chips, vacuum systems, cryogenic systems, photonic modulators and frequency converters and atomic vapor cells.

→ Objectives by 2027 - 2030

- In general, reach the commercialization of quantum sensors for instrumentation.
- Quantum sensors are integrated into larger systems and are key elements of their overall performance, where they leverage their added value.
- Extend the range and variety of commercial products, such as magnetometers medical imaging, quantum-enhanced super-resolved and/or sub-shot-noise microscopes, high-performance optical clocks and atom interferometers, quantum LIDAR, and applications in geoscience, navigation and reference systems as well as earth and climate monitoring.
- Development of networks of quantum sensors as well as space-borne quantum-enhanced sensors, including optical clocks, atomic and optical inertial sensors.
- Establishment of custom processes in foundries on key technologies to provide access to innovations for a larger basis of researchers and companies.
- Integration of quantum measurement standards for self-calibration in instrumentation.
- Continued evolution of enabling technologies and material engineering to increase TRL.
- Develop appropriate quantumness quantifiers and standardized measurement techniques for quantum light used in practical quantum-enhanced measurements, imaging and sensing.
- Demonstration of quantum properties of microwave field for sensing.

Recommendations

- Foster collaboration between academia and industry for development of a complete value chain in each major category of quantum sensors and each quantum modality.
- Strengthen European industrial capabilities in all relevant quantum sensors technologies with performances beyond classical analogues.
- Develop a quantum sensing toolbox: a catalogue of European high-performance sensors/devices that potential buyers can access for understanding how they are suited for, and can be implemented into, their existing production lines and services.
- Support the development and market introduction of high TRL quantum sensors through public procurement, such as the development of a quantum sensor network in coordination with EuroQCI.
- Engage pilot lines to stimulate quantum sensor development and testing.
- Support the development of a metrology and testing infrastructure strictly connected with standardization bodies to build a complete quality assurance chain validating the quantum sensors entering the market.

1.5

General recommendations transverse to the four pillars

This section gathers recommendations that already appeared in parts 1.1 to 1.4, but clearly have a transverse character. For this reason they may deserve special attention.

1.5.A: Recommendations related to hardware

- Consolidate the quantum communication and quantum computing activities, to scale up the capabilities of both pillars in a synergetic fashion.
- Focus on noise suppression and increase the total qubit count.
- Development of control systems based on electronics conventionally placed at room temperature as well as at cryogenic temperatures electronics.
- Increase the number, density and connectivity of qubits while demonstrating improved performance. Improve quality of qubits, including better coherence times and gate fidelities, targeting 99.9% for both one- and two-qubit gates on a scalable, multi-qubit quantum processor by 2027.
- Build up European infrastructure, know-how and a supply line for the fabrication of quantum hardware.
- Development of light-matter interfaces and frequency converters.
- Development of efficient sources of entangled states.
- Optimization of chip to fibre connections to achieve near zero coupling losses.
- Foster the uptake of key enabling technologies for quantum computing, simulation, communication and sensing.
- Develop industry grade quantum nodes and memories to allow operations in real-world environment and integration in the current classical landscape.

1.5.B: Recommendations related to software

- Standardization of a framework of compilers, assemblers and libraries interfacing hardware and software stack.Develop the needed programming interfaces (in the form of APIs and languages) to support easy access from developers, in particular, novel approaches that require direct access from host systems to QC platforms, as this is key for HPC-QC integration.
- Build collections of use cases with reference implementations.
- Development of Europe-based cloud quantum services.
- Development of resource-efficient verification, certification and benchmarking procedures
- Support open-source developments to create operating systems, languages, compilers and software tools.
- Development and analysis of device-independent scenarios.
- Integration of classical and quantum processes.
- Identify practically relevant problems in which a quantum advantage is expected.
- Support the development of open standards to link projects better and to make tech transfer easier.

1.5.C: Other recommendations

- Creation of cross-cutting instances allowing communication between the Computing, Simulation, Communication and Sensing communities.
- Development of instances allowing communication between classical and quantum forces.
- Foster collaboration between academia and industry for development of a complete value chain for quantum technologies and for identifying precise needs and expectations from industry partners.
- Development of a research framework towards energy-efficient quantum devices and foster a European community of experts caring about the physical resource cost of emerging quantum technologies, and willing to develop scientific approaches to estimate and minimize these costs.
- Keep access to resources democratic and affordable.

Part 2

Quantum Resources, Innovation, Industrialisation, and Societal Impact

Cross-cutting topics are essential to the development and competitiveness of the European quantum research and innovation areas. This section outlines necessary actions across ten different such areas, which range from basic science to the development of standards and intellectual property, as well as diversity and ethical issues.

2.1

Basic quantum science

It took several decades until fundamental ideas and concepts in quantum theory, such as Bell's theorem, were acknowledged by the scientific community, as demonstrated by the 2022 Nobel prize. Now they are developing into applications, making the EU a key place for quantum science and technology. This would have not been possible without strong support for basic science research.

Basic science attracts curious and ingenious students looking for scientific challenges. Besides its intrinsic value, basic science provides a nursery for well-trained, yet also flexible, "quantum engineers", which fills the growing demands of a future quantum industry whose scope is still difficult to predict. Now there is a lack of a quantum workforce, 20 years ago, basic quantum research was seen as obscure. We do not know exactly which workforce is needed in future - basic science education prepares them best for these unknown challenges.

Basic science research is key for future technology developments, funding technology development without funding basic science does not work in the long run. Semiconductor electronics would not have matured so quickly and replaced mechanical logic or radio tubes, if quantum mechanics would not have been explored with large efforts decades before, with visionary researchers realizing the tremendous potential of electron waves in crystalline lattices. Equally, or even more, basic science research is very much essential for present-day and future quantum technologies - also because it is not yet clear which particular quantum technology will enable breaking the scalability barrier, and different technologies are needed for different quantum technology applications.

Current collaborative R&D quantum technology projects funded by the EU are the result of previous fundamental research funding - to continue this in future, funding of collaborative fundamental research is essential. Breakthroughs need collaboration of complementary fundamental researchers - pan-EU projects are essential, not only ERC-funded projects.

Basic science funding is effective - it is well known that the cost of funding basic science is essentially negligible compared to the cost of translating results into high-TRL products. The outputs of basic science should be considered as the raw material: even though it is relatively cheap, it is absolutely crucial and key for technology-based economic growth. By keeping basic research alive, Europe shields its strategic agenda in quantum technologies against unexpected upcoming changes of paradigm, and has a chance to introduce such changes itself. In brief, basic science is a worthwhile investment, for sure on human knowledge, but also on purely economic grounds.

2.1.A: Basic science for quantum technologies

For Europe to stay at the forefront and be ready to address upcoming societal challenges, in particular those that cannot be anticipated today, investing in basic science research is the only possible strategy.

While some quantum technologies have reached a significant level of maturity and even reached the market, it is crucial to pursue the study of open scientific questions – both experimental and theoretical – in order to develop more applications, and to ensure flexibility in the evolution and long-term impact. New science provides new ideas for quantum technologies, but their development also stimulates new questions to be answered by new science. This part is broad and covers many different fields. While far from being complete, the following sections identify different areas because of their strategic relevance:

2.1.A.1 Basic science for improved quantum technologies

All quantum technologies of today face fundamental-physics challenges, mostly on efficiencies, fidelities, or decoherence. Better knowledge of the underlying physics will improve the performance of quantum technologies – here some examples:

Photonic quantum technologies and hybrids
For technologies that rely on photons to take off, novel concepts, materials, and platforms should be developed that allow for increasing the complexity of quantum states of light, for example, by scaling up the number of interacting photon states or by generating photonic multi-photon states, e.g, cluster states. Improvement of cavity or waveguide-based light-matter interfaces is essential to achieve non-linear regimes and exploit the scalability potential of integrated photonics, as well as making quantum light sources compatible with complementary quantum technologies, e.g., by coherent interlinking them with internal degrees of freedom of materials and matter qubits. This could be achieved by adjusting the photon and source properties such as bandwidth and emission wavelength. To this end, residual decoherence channels in quantum emitters need to be understood and controlled, undertaking fundamental studies of these systems. Photonic quantum technologies also enable access to high-dimensional quantum information processing using degrees of freedom such as transverse space, time, frequency, and path. Therefore, methods should be developed to enable efficient creation of such states, in conjunction with methods for noise-robust transport over optical fibers and free space.

Spin qubits
Spin qubits in solid-state materials would profit from basic research regarding improvement of qubit coherence time, spin-photon entanglement efficiency and rate, by improving the purity of existing and searching for novel materials, optimizing interfaces and developing alternative protocols. This also includes atomic frequency combs in ion-doped and molecular crystals for quantum memories. Topologically protected spins, e.g., single-triplet qubits, require high-level fabrication and novel designs.

Atoms and Ions
Scalability and performance enhancement requires novel approaches. These include efficient laser or sympathetic cooling of large (1D, 2D, and 3D) ion crystals, methods for qubit detection that do not induce ion heating, novel interaction mechanisms that increase the interaction distance and speed, novel quantum

gates for large systems and high-dimensional qudits. To this end we anticipate the need for novel electric, magnetic, and optical traps, and understanding of residual decoherence due to surfaces. Hybrid quantum systems can be used to increase the number of tools available in quantum simulation and computation. Examples of interactions are atom-molecule, atom-ion, atom/ion-Rydberg, dipolar or non-dipolar spin-exchange. The experimental efforts should be complemented by the development of novel quantum applications for simulation of open (dissipative) quantum systems and molecular dynamics. Choosing the ideal ion or atom for the specific application (e.g. quantum metrology) requires improved understanding of new species. Use of quantum inertial sensors and clocks for fundamental physics research and tests of the fundamental laws of physics will broaden our understanding of fundamental symmetries or even dark matter. Finally, the development of CMOS-compatible atom chips is essential to the possibility of very large-scale integration of atomtronic devices.

Superconducting quantum circuits
Improving and scaling up qubit control, gates, and readout is a paramount issue that connects to basic-science questions. Decoherence in Josephson junctions, related to e.g., two-level systems, must be understood and/or controlled better, new junction materials studied, and steps towards higher-temperature superconducting quantum technologies need to be explored. New fundamental concepts are also needed for scalable architectures based on digital-quantum hybrid systems.

Mechanical and opto-mechanical systems
Quantum states of high-quality mechanical resonators have exceptional coherence time and enable quantum-coherent coupling over many orders of magnitude in frequency, from MHz to optical quantum states at hundreds of THz. This platform opens to fundamental studies at the interface between quantum mechanics, thermodynamics and gravity. In particular further investigation is encouraged towards addressing the decoherence problem, entanglement of massive bodies, thermodynamics in the quantum regime, test of candidate theories of quantum gravity, etc.. They have an obvious application perspective of mechanical sensing at the quantum limit. Basic research is needed to exploit the potential, such as to create multi-partite nonclassical states between many mechanical resonators for networks of quantum-enhanced mechanical sensors.

Quantum architectures with ballistic electrons
Electrons in nearly noiseless environments such as on top of solid neon is a novel promising approach that requires fundamental research to develop methods for initialization, control and read-out of quantum states. On the other hand, free-flying electrons might simplify qubit wiring significantly due to Coulomb interaction, progress in nanotechnologies and nano-photonics have recently given a glimpse of the potential of free electrons by demonstration of photon-electron quantum-coherent coupling in free space.

Topological electronic excitations
Topologically protected quantum states include Majorana states and non-Abelian anyons – both have the promise to intrinsically avoid local noise that is affecting all conventional qubit technologies. Unlike Majoranas, non-Abelian anyons emerge already in exotic fractional quantum Hall states and could be used for universal topological quantum computation. Such fractional quantum Hall systems include graphene-based van der Waals heterostructures and high-quality GaAs semiconductor 2-dimensional electron gasses (2DEGs). In particular hybrid quantum material platforms enable engineering of such topological excitations together with ultrafast modulation and coupling to photons for read-out.

Molecular qubits
Molecules, electron and nuclear spins of their constituents enable functionalities beyond single atom or ion, or quantum dots: they combine a precise design (synthesis) with

the tunability of their properties, including protection of nuclear spins in molecular cages, for instance Posner molecules. Their tunability might enable interfacing to circuit-based quantum technologies, and their excellent optical properties could enable novel interfaces for quantum interconnects. Molecular magnets are also beginning to show promise as spin qubits, with optical initialisation and detection of quantum spin states having only recently been demonstrated. An emerging key characteristic is that their multi-level structure and tunability is very promising for using them as qudits with a sizeable number of levels d. For instance, it has been recently shown that a single molecular qudit can encode a qubit with embedded quantum error correction. Moreover, molecular qudits can be useful as quantum simulators of problems involving quantum objects with many degrees of freedom like bosons. At last, molecular magnets can be exploited as quantum sensors that could be chemically functionalised to bind very close to targets, allowing for improved sensitivity relative to solid-state platforms such as NV centres.

→ Objectives (-2030)

- Generation and control over 20-100 photonic qubits.
- Implementation of a 2D ion trap architecture with >500 qubits.
- Identification and characterization of novel materials for specific qubit applications, such as spin-photon interfaces, superconducting materials or tunnel junctions.
- Demonstration of a second-range mechanical quantum memory with frequency transduction capabilities from MHz/GHz to optical frequencies.
- Demonstration of topological quantum computation using fractional quantum Hall states.
- Survey and characterization of molecular electronic and nuclear-spin qubits.

Recommendations

- Setup dedicated fabrication facilities for highest-quality device fabrication (such as III-V MBE for single and entangled photon sources, spin qubits, oxides for novel Josephson junctions, and nitride facilities for single photon detectors).
- Development of efficient methods to characterize multi photon entanglement to test suitability for quantum applications.
- Setup dedicated fabrication facilities for microfabricated ion and atom chips, including integrated optic control and detection and electronics, to enable research and testing of novel architectures for atoms and ions.
- Invest into fundamental research to improve coherence and scalability of quantum emitters architectures
- Develop mechanical quantum systems, novel electronic systems including topological systems, and molecular qubits.
- Develop further the concept of hybrid devices that combine at least two different systems in order to combine strengths and reduce weaknesses.

2.1.A.2 Basic science to broaden the boundaries of quantum mechanics for quantum technologies

Quantum mechanics is a theory or model that describes microscopic systems exceptionally well. Sometimes it is forgotten that it is not rigorously known why the macroscopic world appears so "classical". Working towards this fundamental-physics question and more in general about how the quantum phenomena manifest in different physical scenarios is crucial to understand the impact of quantum technologies.

Quantum decoherence

Quantum decoherence denotes the effects associated with the loss of quantum mechanical coherence due to the interaction of the system of interest with its environment. Its understanding however is hampered by the same arguments why quantum computing can be advantageous compared to classical: we cannot calculate, predict or model the thousands up to uncountable quantum systems of the environment. Yet decoherence is not always an enemy. Intensive research over the past few years has made it clear that decoherence can speed up some processes, help generate entanglement, or be useful for rapidly eliminating unwanted branches of the wave function. The objectives of the research are therefore twofold. On the one hand, one aims at mitigating decoherence effects, as they hinder the efficient performance of quantum tasks and applications. On the other hand, one would like to use decoherence effects in those situations where they can be exploited for specific and selected quantum operations.
Two (related) points emerge:
The first one is that most models of decoherence are "fixed", in the sense that one derives an effective noise model, or simply fits such a model phenomenologically. Then, one pretends that this effective model is an accurate description of the physical system under consideration. Traditionally this approach has worked well, probably because one was simply interested in basic physics, rather than realistic quantum technology. But now we want to use the physical device, which means we start applying driving, control, error correction, and the like. This is where the interplay between noise and control comes into play: the derived effective model is simply no longer valid in the presence of controls. In this framework, even basic and popular control techniques, such as, e.g., spin echo, cannot be properly understood and described.

The second point is that the overhead of error correction is still vast - requiring a large number of physical qubits for a single logical qubit - to be feasible. If we want to use quantum technology soon, we need to find more effective codes.
A promising avenue is to use the structure of the noise (particularly bias), where it has been shown that improvements of several orders of magnitude can be found. But this requires to design bias-preserving controls, that is, controls which leave the structure of the noise intact.

Quantum thermodynamics

Thermodynamics is a very successful theory that has led to the development of many important technologies, from engines to refrigerators. Understanding how thermodynamic laws are modified by quantum phenomena is an active research direction, with implications also from an energetic point of view. Thermoelectric energy conversion, for instance, has many important industrial applications from heat pumps to Peltier elements, but all known bulk thermoelectrics have relatively low efficiency, motivating the search for more efficient thermoelectric materials that are structured on the nanoscale. In low-dimensional structures, quantum effects can play a significant role and are known to allow for increased thermoelectric efficiency. Funding further research in quantum thermodynamics – a field in which Europe is far more prolific than America or China – could lead to more efficient energy conversion devices that exploit quantum-mechanical effects such as entanglement and superposition to achieve hitherto unimagined functionalities. NISQ devices may also provide a perfect testbed for quantum thermodynamics, and search for efficient nano-engines and batteries.

Condensed matter

When we abstract from the search for rigorous quantum advantage, most of the quantum computing devices (digital quantum computers, analogue quantum simulators, quantum annealers, etc.) may serve as quantum special purpose computing devices to solve problems in various areas of science. Note that in such situations fault tolerant error correction does not play an essential role. Errors and decoherence, which typically being nuisance, here might turn out to be an opportunity, allowing to mimic disorder or noise always present in realistic experimental systems. At this stage, most of the applications occurs in fundamental problems of physics. Particularly important are applications to study dynamics of strongly correlated quantum many body systems. This concerns, in the first place, relevant models of condensed matter, pertaining, for instance, to high T_c superconductivity, strongly correlated topological systems, quantum disordered systems like those exhibiting many-body localization, Majorana fermions and topological computation, twistronics (i.e. twisted bilayer graphene-like) systems etc. Recently, there has been considerable interest in applying quantum computing devices to simulate systems relevant to high energy physics, such as lattice gauge theories. Some simple experiments mimicking matter and quantum electrodynamic fields have been realized in the last years. At the same time, the same problems have also been attacked using classical tools. Quantum insights have led to the development of more efficient numerical methods for the simulation and understanding of phenomena observed in many-body quantum systems, such as those based on tensor-network states.

Quantum gravity

Quantum technologies are built on the assumption that quantum physics holds for arbitrarily complex systems, provided they are sufficiently isolated. That is, any system can exhibit quantum phenomena in the absence of decoherence, namely unwanted coupling to the environment. This assumption is certainly supported by experiments performed to date, however it is not clear if it holds also for objects of significant mass starting at around a microgram – since there is no unified theory of quantum mechanics and gravity yet. It is not known if spacetime quantum superpositions exist, and if they lead to a fundamental reduction of the quantum state. Working towards this is crucial for large-scale quantum technologies, but also for understanding and controlling classical decoherence.

→ Objectives (-2030)

- Comparison of decoherence models with algorithms on noisy quantum computers.
- Improved understanding of the quantum-classical transition and decoherence mechanisms.
- Characterize and optimize the thermodynamic efficiency of quantum information processing.
- Develop a deeper understanding of strongly correlated quantum matter systems.
- Identify and narrow experimental parameter regions where quantum gravitational effects become relevant.
- Explore novel concepts and systems where quantum technologies can be an advantage, e.g. in biology, chemistry and thermodynamic systems as well as across the established application areas.

Recommendations

- Investment into fundamental research of foundational questions connected to quantum technologies, which in turn will result in strategies to improve quantum technologies.
- Investigate the many facets of decoherence. Select more viable and more general strategies that can be effective in different situations.
- Characterize the interplay between noise and control.
- Extend and consolidate the application of quantum information concepts and tools to more disciplines, such as, e.g., thermodynamics, condensed matter or quantum gravity.

2.1.A.3 Basic research for quantum information theory

Foundational questions on quantum algorithms and software

It is not clear yet which problems of real-world importance are suitable for present-day or near-future quantum computers, nor where a genuine quantum advantage can be expected. The development of quantum software is a highly active field that is increasingly driven by the desire to solve problems of real-world importance on quantum computers. Basic research into the fundamental properties of quantum algorithms is required to put these efforts onto a solid foundation and provide a clear picture of where genuine quantum advantages can be expected.

The first step is to compare the algorithmic complexity of the newly designed quantum algorithms. It is expected that the first algorithms showing a practical quantum advantage will provide an exponential (or super-polynomial) speedup over the best-known classical alternatives. It will then be necessary to look at developments required to transform the theoretical speedup into a practical speedup, such as how to optimally encode large amounts of classical data for quantum machine learning, and how to efficiently represent trial functions for classical optimization problems, how to reduce the number of shots when measuring expectation values on quantum registers, or and how to minimize the overheads required for fault tolerant quantum computing. Similarly, advanced algorithms for quantum metrology that enable high-precision measurements in distributed quantum network systems will benefit from insights into the fundamental properties of quantum noise in many-body systems and novel methods for suppressing it.

Quantum complexity theory

Quantum complexity theory aims to rigorously prove quantum advantage and to rigorously bound its limits and determine the conditions under which it can be achieved – and it contains very important open questions, with implications on possible quantum advantages in quantum technologies as a whole. Fundamental research not only makes progress in understanding complexity classes and how quantum advantage depends on noise, but also leads to the exploration of novel quantum algorithms for specific applications, including classical-quantum hybrid approaches.

An important current challenge for quantum complexity theory is to provide a solid theoretical understanding of the current quantum advantage experiments and near term (hybrid) quantum computing. Complexity classes and query complexity are two possible frameworks for that. The current quantum advantage experiments use quantum computers with 50-100 qubits and this number is just slightly beyond what can be simulated classically. Providing evidence that the performed experiments are hard for classical computers requires new complexity assumptions and, possibly, new proof methods. At the same time, it should be possible to build on the rich foundation provided by classical and quantum complexity theory. Hybrid computation attempts to exploit the power of relatively small quantum computers by using them in combination with a classical high-performance computer. Building a theoretical foundation for such computation is highly relevant and can guide the practical work in this area.

In several areas (including the analysis of quantum advantage experiments), it is important to develop fine-grained complexity methods which allow to prove very precise lower bounds on the classical or quantum complexity, under simple-to-state assumptions. Such theory exists for many classical problems but needs to be extended to the quantum case in a systematic way.

Quantum information and resource theories
Quantum information theory focuses on the properties of information contained in quantum states. It can be seen as the theory providing the quantifiers, inter-conversion laws and trade-offs among resources in quantum phenomena for quantum information protocols.

An important outcome of quantum information theory is that many applications rely on correlations with no classical analogue, such as entanglement or Bell non-locality. In other words, that quantum degrees of freedom share some form of correlation that cannot be produced classically. It is widely accepted that the advantage of quantum computers over their classical counterparts relies greatly on their ability to encode and handle information via entanglement.

Entanglement comes in different flavours, which depend on how to split the quantum systems into different relevant components (e.g., for a quantum computer, such natural relevant parts are the qubits). The most well understood flavour is bipartite entanglement, that describes entanglement between two parts. Bipartite entanglement is relatively well understood at the theoretical level. However, the notion of multipartite entanglement, describing entanglement between many parts–e.g. many qubits–is more elusive, and is an object of discussion and investigation. Since the dimension of the Hilbert space of the total system scales exponentially with the number of its subsystems, the concept of multipartite entanglement, shared among all the parts of a given system, is related to complexity. Two major research-problems are:

- To better understand and classify current measures of multipartite entanglement;
- To define new measures of multipartite entanglement, easier to manipulate while still informative.

The complexity of entanglement is a cutting-edge topic in quantum information science and quantum computation, as well as in condensed matter physics and quantum field theory. In fact, in quantum computation, it measures how hard quantum computations are to simulate on a classical computer, therefore quantifying quantum advantage. In condensed matter, multipartite entanglement measures can serve to detect topological phases which are useful e.g. as protected quantum memories, and for producing fault-tolerant schemes for quantum computation. More generally, comprehension of entanglement in condensed matter systems, quantum field theory and high energy physics has benefited from the fields of quantum information and computation.

Similar considerations apply to other quantum resources of relevance for quantum information processing, such as Bell nonlocality, secret bits, random bits, coherences, magic, ...

→ Objectives (-2030)

- Identify clear criteria for quantum advantage with simple noise models, for discrete and continuous-variable quantum information processing.
- Development of novel quantum algorithms testing quantum advantage.
- Design efficient methods to detect entanglement and Bell non-locality in quantum systems.

Recommendations

- Improve our understanding of the relationships between quantum advantage and entanglement harnessing.
- Support research on fundamental components of quantum algorithms (including near-term/hybrid algorithms) and rigorous analysis of them in terms of complexity theory.
- Invest into fundamental research in theoretical quantum information to answer these deep questions, where the answers could change the direction of quantum technologies as a whole.
- Relate multiple flavours of entanglement to computational complexity, and to study the evolution of entanglement through quantum algorithm execution.
- Expand our understanding of known quantum resources.

2.1.A.4 Energy cost of quantum information processing

As quantum technologies drive strong expectations from governments and industries, a responsible way of deploying them must include the study of their potential for energy savings and contained environmental footprint. At the present time, reduced energy consumptions have been noticed on various NISQ processors over the world (trapped ions, superconducting qubits, neutral atoms...). While these observations seem to point toward an energetic advantage of quantum nature, the physical mechanisms behind them are barely understood: how does energy consumption scale with the processor size? How does it relate to the computational performance or the qubit technology? How does it compare to classical processors? Beyond quantum computing, the understanding must include quantum communication, quantum sensing and metrology.

In the quest for energy savings, efficiencies are beacon lights. Defined as the ratio of the performance over the energy cost, they are bound to become major figures of merit in our finite world: indeed, increasing them holds the promise to implement identical tasks with fewer physical resources.

In quantum technologies, the performance of quantum processes is optimized at the quantum level. One natural way is to mitigate noise: these efforts involve a large range of expertise, from qubits fabrication, quantum thermodynamics, quantum control, thermo-electricity, reservoir engineering, to quantum information sciences and quantum error correction. Conversely, energy costs are set at the macroscopic level by enabling technologies (cryogeny, electronics, cabling, lasers, ...). Thus, optimizing the efficiency of quantum technologies requires to articulate fundamental research and engineering within an interdisciplinary research line.

Once a proper framework is established to estimate actual and theoretic energy consumption of quantum processes, one can start benchmarking quantum technologies and compare them to their classical counterpart. This will allow responsible and planet-respectful development of quantum technologies. This will also fuel the search of another type of quantum advantage over current technology: an energy advantage. If tasks can be done more efficiently using a quantum process, this might have tremendous implications on quantum technology development. Conversely, knowing which task can be done more efficiently with classical technologies will prevent unnecessary investments in quantum counterparts. This knowledge will be crucial in the years to come.

Recommendations

- Define energy-based metrics for all quantum technologies; provide methodologies to measure them and establish benchmarks.
- Derive fundamental bounds for energy consumption; draw out roadmaps and design practical and basic scenarios to minimize the energy costs of quantum processes.
- Use energetic efficiencies as optimization tools to operate smart technological choices as quantum devices are being built, to anticipate and avoid dead-ends of energetic nature.
- Understand the impact of hardware, software as well as quantum and classical control on the energy consumption of real quantum devices.
- Define and provide the conditions of an energetic advantage of quantum nature, where useful quantum devices consume less energy than their classical counterparts.
- Foster collaborations of researchers from thermodynamics, classical computer sciences, quantum computing and other relevant energy-linked disciplines.

2.2

Engineering & enabling technologies

Quantum technological systems contain far more than the quantum core – they need to be integrated into large systems and encompassing all the classical subsystems needed for their interfacing with the classical world operations. This defines the enabling technologies and engineering that are required for their implementations and operations. These involve important cross-cutting activities concerning the development of transversal technologies of relevance for all the pillars. These activities include, among others:

Manufacturing, testing & packaging

The development of many quantum technologies at scale requires access to industrial-grade micro- and nano-fabrication facilities, providing the necessary resources and capabilities for the manufacturing and packaging of quantum and classical devices. Closer heterogeneous and monolithic integration between quantum and classical devices is needed, possibly pursuing all opportunities for the co-integration within all-in-one quantum-classical technology platforms. Technology process optimization, design for reliability, manufacturability and testing are key for quantum technologies, especially at very low scale dimensions, and covering all development on different length scales (from atomic length scales to microsystems level and beyond) especially at very low scale dimensions. Alongside manufacturing and integration technologies, thermal management, shielding and packaging have to be optimized. Furthermore, reliable ways to quantify material properties (e.g. microwave/optical losses, flux noise, two-level-system density, etc.) and how they translate to quantum circuit devices and gate performance are also needed.

Devices & components

A wide variety of devices and components are required to deliver complete systems. This includes photonic and electronic integrated circuits (e.g. field programmable gate arrays, integrated photonics), electronic, photonic and optical devices (e.g. high-end lasers, cavities), electronic control equipment (e.g. low-noise microwave components, waveform generators), and refrigerators providing cryogenic temperatures (e.g. dilution refrigerators, cryocoolers). Affordable access to essential device and component licenses for young EU small and medium enterprises (SMEs) is an important issue to enable and protect the growth of the EU quantum industry.

Control and readout interfaces

Finally, quantum-classical system interfaces are required in the form of control and readout subsystems and equipment for high-fidelity quantum operations. Quantum optimal control and readout provides toolboxes that allow one to identify the performance limits for a given device and gate implementations, and it provides the protocols for realising device quantum operations within the expected limits.
With respect to innovation, it is important to distinguish between enabling startups that have new ideas, and scaleups that need to move towards manufacturing. This calls for a careful positioning of pilot lines and other enabling technologies. Some pilot lines can be academic, at lower TRL, supporting proof-of-principle and prototyping efforts. However, some also need to be more industrial, at higher TRL, to enable scaling towards manufacturing. Similar considerations hold for other enabling technologies, such as laboratory equipment, test & measurement infrastructure, cryostats, etc., where some will enable proof-of-principle lab-based implementations, while others will enable production at scale, and need to be compatible with standards.
Another consideration in the longer term is the assessment whether an (enabling) technology will be vertically integrated into a quantum technology company. This can be the case when it is (highly) specific, requires particular skills, and/or when it represents core intellectual property. On the other hand, when the technology is generic, and/or costs are too high for individual quantum technology companies, we should consider whether it should be made accessible in a horizontal business model, using pilot lines or similar infrastructure. Targeted EU investments should ideally also take this broader perspective into account.

2.2.A: Ongoing engineering initiatives

Several large engineering activities are currently taking place in the EU, which we will briefly summarize here. Further initiatives addressing specific directions toward the grand challenges targeted by the large initiatives are also mentioned in relation to their key specific aspects.

Within the Quantum Flagship, new initiatives were launched to support quantum pilot lines as well as testing and experimentation, through two dedicated Framework Partnership Agreements (FPAs), which have now progressed to first Specific Grant Agreements (SGA) in spring 2023. They represent the first step towards the implementation of the activities described in the previous paragraphs.

Quantum Pilot lines (Qu-Pilot)- The Quantum Technologies Flagship Initiative, with the support of the RTOs, is establishing the first quantum pilot lines, to bring together the different and proprietary quantum chip and component design and fabrication processes to achieve harmonization and compatibility with the existing manufacturing infrastructures. The quantum pilot lines are critical for implementing a path from the R&D to Industry communities. Qu-Pilot fosters the growth of European quantum industry by aiming to quantum microsystem pilot-line services.

The pilot line initiative is aligned with those needs:

- Technologies developed within the quantum flagship that need to scale up towards manufacturing
- Demand of fabless quantum technology businesses (i.e. companies focusing on the design of QT rather than their actual fabrication) requiring critical infrastructure support for product development.

That also includes foundries able to manufacture the required technology, including superconducting and semiconducting qubits for quantum computing, integrated electronic and photonic circuits for quantum computing, communication and sensing, superconducting electronics, diamond devices for quantum sensing and computing.

Testing and experimentation (Qu-Test)- Qu-Test is a federated network of testbeds located at European RTOs and National Metrology Institutes (NMIs). The network brings together competences and infrastructures to offer testing and validation services to the European quantum industry, including the components produced by the pilot lines. A first goal of this cooperation is to support the creation of a trusted supply chain through the validation of quantum chips, devices, components and systems provided by the industry community. After an initial ramp-up phase that will see close cooperation with industry to agree on requirements and processes, the testbed network is set to provide in the long term testing and characterization as an independent commercial service. A second goal is to discuss and agree among RTOs and NMIs on unified sets of parameters to characterize quantum devices in the areas of quantum computing, communication and sensing. Methodologies and procedures related to the metrology of quantum devices will be harmonized within the network, making a critical contribution towards the creation of standards for quantum technologies.

In order to fulfil their mandates, the application and technology-specific FPAs and SGAs, such as OpenSuperQplus, focusing on superconducting qubit based quantum computing, also include engineering activities. Further, so-called European level Joint Undertakings (JU), such as the ones for Key Digital Technologies (KDT), Electronic Components and Systems (ESCEL) and Chips, also fund large scale collaborative projects. One example is the ESCEL project MATQu (Materials for Quantum Computing), which focuses on components and materials for superconducting quantum computing.

2.2.B: Quantum Technologies and the Chips Act

This section is presenting a vision towards the European Chips Act. The topics of interest as expressed in the SRA and SIR are aligned with the Chips Act plan for action, as expressed in its Staff Working Paper V2. The main question is: “What kind of dedicated chips and/or chips technologies are needed for quantum technologies?”

Quantum technologies require the development of very specific chips. It is for example the case of silicon-spin, superconducting, or photonic circuits for quantum computing. In addition, the development of quantum technology requires numerous advanced classical chips technologies, considered as enabling technologies.

In a general manner, both the SRA and SIR stressed the importance of a strong coordination between the chips industry, foundries and infrastructure on quantum computing, from the fab level and process up to design methods and tools. This is required to develop an integrated tool-chain (design to processing) and module libraries for integrated photonics, cryogenic and superconductor electronics, including coherent optical-electronic converters.

Consequently, we consider the alignment of the Research and Industry roadmaps for quantum technology towards the Chips Act along two tracks:

- 1. Technologies for dedicated quantum chips, required to fulfil the quantum challenges. Those technologies are relevant for specifically quantum devices.
- 2. Classical chips technologies for quantum (enabling technologies)required to support the industrialization and scaling of quantum technology. Those technologies are generic (although specific development are needed) and used in other fields. (Chips-Act WP, pp. 56)

2.2.C: Technologies for the design and fabrication of quantum chips

The plan for actions of the Chips Act (Pillar 1, § 8.1.6) sets an action for “Investing in Advanced Technology and Engineering Capacities for quantum chips”. Below we address the three main sections present in the current document.

- ***Innovative design libraries for quantum chips (EDA Tools, including heterogeneous processes)-*** The aim is to secure the design and fabrication processes of quantum chips in the EU using the most advanced process capabilities of the semiconductor industry for classical chips. (Chips-Act-SWP V2, p. 68).This quantum specific action shall be coordinated with the EDA (Electronic Design Automation, i.e. design toolchain) tools action of the Chips Act. Design tools and libraries allowing the support of quantum technology and their integration with classical ones are required. Novel design methodologies and tools are especially important for quantum technology. Just like is the case in microelectronics, such EDA tools will be the result of a co-development process with the technologies themselves (Chips-Act WP, p. 52). On top of qubit platforms compatible with the processes of the classical semiconductor industry (electronic- and photonics-based qubits), standardised design libraries and fabrication processes should also be developed for alternative qubit platforms (superconductor-, diamond-, ion- and atom-based qubits). The goal is thus to develop an integrated toolchain (design to processing) and module libraries for integrated electronics, photonics and optics, cryo- and superconductor electronics, including high-transmission photonic chips, and coherent optical-electronic converters. It would be most desirable to transfer know-how from academia using open Process Development Kits (PDKs) and/or advanced industry-academia cooperation models.

- ***Quantum Pilot lines-*** To move quantum pilot lines and testing forward, we need to find synergy with existing players in the industry arena (Chips-Act-SWP V2, p. 68). Pilot lines should enable modules or packages where quantum circuits and control/readout electronics can be integrated, either monolithically or through a heterogeneous approach, and for providing access to dedicated clean rooms and foundries for prototyping, production and packaging, thereby reducing the entry barrier for the development and production of small volumes of quantum components and accelerating the innovation cycles. There is need to align the activities carried out within RTOs (Research and Technology Organizations) with those expected to be done in foundries when there will be a need to scale the technology quickly. Timely transfer of processes and know-how from RTOs to foundries located within the EU will be critical for success of European quantum hardware industry. The ongoing Qu-Pilot initiative, presented earlier in this chapter, is a strong start but this needs to be up-scaled and widened towards the participation of industrial foundries and other enabling technology industries to maximize the future impact and benefits. Co-innovation and co-development of pilot lines, with a federated approach as taken in Qu-Pilot,will be essential for that. Finally, in terms of critical raw materials, it will be essential to secure a reliable EU supply of isotopically purified silane gas (Si-28H4) for the production of isotopically pure silicon wafers, as well as Ge-72 and other isotopes.

- ***Testing and experimentation-*** To advance testing and experimentation it is required to invest on facilities and know-how. Quantum chips require both in-line testing during production and end-of-line testing in an intensity that is, due to the requirement of quantum coherence, a lot higher than for classical chips. Also, testing and experimentation of quantum chips requires complex calibration procedures at cryogenic thermal regimes, resulting in a substantial exacerbation of the challenges with respect to the classical chips. In most instances, for example due to operating environment and conditions, the development of dedicated testing equipment together with measurement traceability chains is and will be required. RTOs can develop that dedicated equipment for quantum device testing together with industry and it is crucial to support this cooperation. At the same time, it is of paramount importance to support efforts on standardization of quantum technologies and specifically to support industry in taking part to working groups and technical committees at standards developing organisations such as CEN-CELENEC, ISO, etc.. Standards will establish a unified way of working in the quantum industry community. This is a required step to move the testing of devices from RTOs or NMIs to accredited testing and calibration laboratories operating in the testing, inspection and certification market. This will become the European quantum measurement and testing infrastructure that has inQu-Test initiative, presented later in this chapter, is the first step towards the implementation of these facilities.

2.2.D: Electronic circuits and electronic integration

Besides the three actions proposed in the previous paragraph, it would be beneficial to specify other actions in the Chips Act related to all classical chips technologies that are required for the development of a quantum ecosystem.

- ***More than Moore*** –Integrating various functionalities (digital, analogue, mixed-signal, microwave, photonic, etc.) and implementation technologies (various substrates), also known as "More than Moore", will be key for the integration of quantum technologies within systems and applications. "The main technical challenges with More Than Moore devices is that they may require unique structures and different materials to those traditionally used." (Chips-Act WP, p. 53). For example how to integrate new materials than semiconductors (e.g. diamond) in existing production lines, and trigger the paradigm shift to the metrological precision required for quantum technologies. So the goal here is to support the testing for high-quality to provide immediate feedback, miniaturization and integration of magnetics, photonics, microwaves and superconductors into the manufacturing process of complete chips. Supposed to include the following: Cryogenic electronics and components for amplification, attenuation, and processing of signals in cryogenic environments, incl. the high-frequency domain.

- ***Packaging***– The development of quantum technology requires specifics chips packaging to accommodate for dense signal pathways, various signals (both electronic and photonic), cryogenics or/and ultra-high vacuum interfaces. Current FPGA-based controllers could be replaced by ASICs and several purpose-oriented and operational environment adapted layers of control. Advanced packaging techniques such as 2D and 3D stacking developed in the context of the Chips Act will be a major asset for Quantum Technologies (Chips Act WP p. 49). Scaling the quality and number of qubits will require advanced 3D architectures as well as assembly techniques that take into account passive and active thermal management. Quantum processors can also require magnetic and radiation shielding.

- ***Testing & validation*** –In terms of testing and validation, we need reliable material performance measurements and mapping to qubit performance, on-chip spectroscopic techniques, harmonized measurement methods and protocols for qubit characteristics. Moreover, we need agreed-upon standards and benchmarking of single/multi-qubit-circuit performance and the development of in-situ measurement techniques for microwave power and time-domain waveforms. This includes for example achievable sensitivity and uncertainty of quantum sensing methods, including uncertainty budgets, and the validation of single charge detectors for qubit read-out by single electron metrology.

2.2.E: Cryogenics and cryogenic integration

For the operation of most quantum technology components, low temperatures with sufficient cooling power (to sustain the required device temperature under operation) is required. This assures the adequate thermal environment for the different electronic and photonic components such as detectors, photon sources, qubits, and qubit control and readout subsystems, which are needed in fully operational quantum technology systems. Several promising quantum hardware platforms require cryogenic cooling below 4K and some even to sub-1 K temperatures. Several commercial suppliers are available for cryostats, with some leading providers in the EU. The cryogenic offering ranges from equipment designed for general purpose to customised cryostats systems able to address some very specific needs of quantum systems. Continuous development efforts are needed to further increase the performance of cryogenics, optimise stack integration and ensure overall competitiveness.

For quantum computing we will need refrigerators with a base temperature that suits the particular qubit platform in question (including interfacing/read-out) and, in general, provides a solution that can be at the same time adapted to scaling-up the number of qubits. In the particular case of solid-state superconducting qubits and CMOS qubits, ultra-deep cryogenics is part of the computer stack structure to offer temperatures in the millikelvin range that are needed to harvest the quantum properties of matter, avoid noise from thermal sources and increase coherence time of qubits. At present, quantum computers are operated with a limited number of qubits and current cryogenic products are able to meet this cooling demand without difficulty. However, the scaling-up of the number of qubit will be accompanied by a significant demand for power at low temperatures (sub-kelvin) requiring the design of a new cryogenic infrastructure optimized to answer the cooling needs for large quantum circuits and qubits needs. On the path towards large quantum communication networks, these cryogenic systems will need to be cost-effective and compatible with use in data centres and/or current telecom infrastructure. For quantum sensing, particular interest is in compact cooling systems. These can be based on combining different stages based on different physical mechanism from laser and electronic cooling to pulse tubes, for examples.

In order to allow for the efficient control and scaling of quantum circuits, the control electronics must be co-located with the actual quantum chips. This includes sample holders, cables, connectors, interconnects, filters, circulators, isolators, attenuators, amplifiers, signal processors (including in the high-frequency domain), and integrated signal multiplexers for scalable control and readout. Overall, increasing the number of qubits that can be simultaneously controlled should go hand-in-hand with the development of quantum processors over the next decade. The fabrication of classical control chips able to operate at cryogenic temperatures (e.g. cryo-CMOS) as well as the fabrication of fast classical superconducting control chips and control of highly efficient single photon and single electron detectors is critical for the development of quantum computing hardware, in order to optimize signal routing, increase qubit readout speed and efficiency. The addition of other new materials into the fabrication process (e.g. III-V group materials, magnetic materials, etc.) could play a significant role in extending the capability of CMOS beyond its current limits and meeting the needs of the quantum technology developments.

2.2.F: Photonics and photonic integration

Lasers have become crucial to quantum computing experiments using cold atoms and ions, and in general for quantum communication and quantum sensing experiments. For quantum computing, ions are typically trapped in electromagnetic traps, for which the ions need to be cooled using cryogenic cooling or produced within the trap by laser ionization followed by laser cooling. This requires frequency-agile narrowband ultra-stable continuous wave (CW) lasers in the ultraviolet, visible, and infrared ranges, at specific frequencies determined by the transitions in the ion. Typically, other narrow transitions need to be controlled with lasers simultaneously, including repumping transitions and sub-Hz level clock transitions. Neutral atoms can be trapped in arrays using optical lattices or optical tweezers produced by high power narrowband lasers with extremely good intensity noise. For these atoms to be used as qubits, they require lasers for gate operations, including laser cooling, repumping, state preparations, clock transitions, lattice lasers, and sometimes Rydberg transition lasers. The CW lasers need to meet a whole set of criteria including high stability, high robustness, frequencies ranging from the ultraviolet into the infrared ranges, and narrow linewidth.

To achieve the so-called SWaP-C requirements for these lasers, semiconductor-based solutions and higher integration will be necessary. However, small volume production in mainly academic or institutional fabrication plants remains a challenge. In terms of innovation, over the next three to six years, we will need to increase the TRL of:

- High-power, narrow-band, phase- or intensity-stable solid-state or dual-frequency fibre lasers
- Integrated laser systems (cooling laser, lattice laser, low noise electronics)
- Clock lasers (narrow linewidth (Hz) lasers coupled to an ultra-stable optical cavity)
- Stabilised lasers for atomic cells, optical frequency combs, and optical cavities

One of the main challenges here is the stabilisation of these lasers – sometimes to the Hz level at carrier frequencies of hundreds of THz. The technique of optical cavity stabilisation has moved from the laboratory into a commercial product and is a crucial component in neutral-atom-based quantum computers as well as optical atomic clocks. Many lasers can also be referenced to optical frequency combs, thus benefiting from both the narrow linewidth and the absolute stability of these combs.

Both CW and pulsed lasers are used for quantum communication applications, both for the generation of entangled states (e.g., in parametric down-conversion) and as flying qubits (e.g., for entanglement distribution between spatially separated trapped atoms). This technology paves the way for long-distance quantum communication and QKD via fibre-optic networks or satellite. The most important challenge in this field is the quantum entanglement of different spectral bands determined by the quantum communication or QKD approach with telecom wavelengths for long distance transfer. For space applications, it may be necessary to research and develop lasers customised specifically for use in the harsh space environment (temperature, shock, vibration, and radiation) and longer lifetimes. Low phase noise and narrow linewidth is crucial to generate high-fidelity quantum repeater links using single-photon entanglement. Different technologies are acceptable if they can be shown to meet the technical requirements. Possible technologies choices might be based on fibre lasers or on diode lasers with extra-long external cavities.

In addition to lasers, quantum technology also requires single-photon sources. These are critical components for discrete-variable quantum key distribution and some types of photonic quantum computing. Some of the approaches used to create single photons may also be used to create pairs of entangled photons, which are needed for quantum LiDAR and entanglement-based quantum key distribution, as well as emerging techniques in quantum-enhanced microscopy and spectroscopy. An ideal single-photon source should emit indistinguishable photons (or photon pairs) on-demand at high rate, with a low probability of multi-photon emission, and should be able to be integrated on-chip.

Next, photon detectors are widely used for many quantum technologies and can be broadly captured in two categories: single-photon detectors and heterodyne / homodyne detectors. Single-photon detectors are required for discrete-variable QKD and photonic quantum computing, some types of quantum imaging, and quantum LiDAR. An ideal single-photon detector should have high detection efficiency, low dead time, timing jitter and dark count rate, and should be photon-number resolving. There are several technological approaches to meet these requirements. Superconducting nanowire single-photon detectors (SNSPDs) are a relatively new technology that offer high efficiency, low dead time, low timing jitter, and low dark count rates, but they also require cryogenic cooling, which can be cost-prohibitive for some applications. Heterodyne / homodyne avalanche photodiodes (APDs) are a more mature technology that is used in applications such as QKD and does not require cryogenic operation. SNSPDs and APDs are not intrinsically photon-number resolving, but superconducting transition edge sensors (TES) and CMOS image sensors that provide this capability are in development. Both types of detectors are commercially available, but more research is required to improve their performance and reduce their footprint.

For the transmission of photons a new generation of waveguides and fibres will be key to successful realisation of several quantum applications. Progress on fibre amplifiers is relevant for amplifying optical frequencies that match the transition and trapping frequencies of atoms used in quantum computers, or for sensing applications. Fibre-amplifier technology is particularly relevant for scaling up cold-atom or ion-based systems. Work to date on fibres has mainly focused on Yb, but the development of less conventional doped or co-doped fibres (Nd, Tm, Tm-Ho, Er, Er/Yb, Raman, Bi, etc.) will open up possibilities for amplifiers able to amplify directly at frequencies relevant to quantum applications, or enable new wavelengths through non-linear frequency conversion. Expertise in fibre micro-structuring (distributed filtering) to privilege unconventional wavelength laser emission will help expand the spectral agility. There is one emerging class of fibre in particular that is expected to play a central role in the quantum systems of the future: hollow core photonic crystal fibres (HCPCFs). These are made of a hollow air core embedded in a photonic crystal lattice and enable enhanced light/ matter interaction over theoretically unlimited distances (fibre lengths), and are likely to emerge as a disruptive innovation in the context of the ongoing quantum photonics revolution. This interaction between quantum objects (photons, atoms, ions, and molecules) has already been exploited in a new class of HCPCF-based photonics objects. Examples include miniaturised microwave clocks based on Rb- or Cs-atom-filled HCPCF, and Rb-filled HCPCFs for quantum memories.

Finally, photonic integrated circuits (PICs) play a crucial role in quantum technology, most notably in communication and computing. It is key to leverage existing PIC technologies as much as possible, to pave the way for scaling, and to limit costs. Technologies that can be leveraged are silicon nitride (SiN), indium phosphide (InP) and silicon photonics (SiPh), micro-transfer printing (µTP), and packaging. SiN enables ultra-low loss operation over a wide optical bandwidth, including the relevant communication bandwidths (around 1310 nm and 1550 nm) and the visible light range (for atom, ion and diamond qubit applications). This technology is mature and available through commercial entities. Due to the simplicity of the PIC fabrication process, it can relatively easily be optimized for the application at hand. InP and SiPh are also available in European commercial companies and their main application lies in quantum communication, using either weak coherent pulse and continuous-variable QKD approaches. It is still an open challenge to integrate (deterministic) single-photon sources and detectors in these platforms. The technological maturity is relatively high, but the path to manufacturability is still in development, as pilot lines have only recently been established and/or are still being set up. Packaging of PICs can be done through established templates one of these pilot lines, although cryogenic packaging is not standardized yet. The current infrastructures support relatively low volumes, which is adequate for most early-stage companies. Newly established pilot lines also include an effort of μTP. Although in an early stage, this technique can eventually support an ecosystem of wider wavelengths and/or quantum-specific components. Indeed, quantum technology can be a sweet spot for μTP, as volumes are relatively low, non-telecom wavelengths are often needed, and specific components are necessary, such as single photon sources and single photon detectors.

2.2.G: Supply chains and critical components

To develop products and services for quantum technology, a secure, robust, and future-proof supply chain is necessary. This means that we should strive towards sufficient production capacity of both quantum-specific and enabling technologies in the EU and a reliable supply of critical components.

The supply chains related to quantum technology are still emerging. Most component suppliers are either SMEs which often started as a university spin-off or larger companies that provide high-tech equipment. According to some estimates, only 2% of start-up investments in the quantum computing domain goes towards component manufacturers1. The current market for quantum technology components is relatively small and the demand mostly comes from publicly-funded or corporate R&D labs. Volumes are low and in many cases custom-made components are required, so prices and delivery times and generally high. Moreover, since most quantum technology setups are designed to push the scientific frontier, only a handful or suppliers will be able to provide the state-of-the-art devices or components that are required, which makes diversification challenging. The explorative nature of most quantum technology systems also result in little modularity and flexibility. As such, standards will be important in developing components that can be used in different settings as well as easier comparison between suppliers.

It is essential to create awareness of these emerging supply chains. This is not limited to just the critical components, but also includes the underlying critical raw materials and semi-manufactured goods. Insight into the current strengths and weaknesses of the European ecosystem from a supply chain perspective is essential for steering strategic investment decisions and alleviating bottlenecks. Preliminary assessments have been made of critical component suppliers, which show that we currently hold a few key positions in the EU, such as for dilution refrigerators, laser diodes and cryogenic cabling. At the same time, we depend on some non-EU countries for other critical components such as FPGAs, helium-3 and certain cryocooler equipment. As complete self-sufficiency will most likely be impossible, and perhaps even undesirable in terms of costs, we should ensure stable (trade) relations with the non-EU countries on which we depend. Simultaneously, we must protect and strengthen our own control points in the supply chain and foster situations based on reciprocity. Monitoring the supply chains over time will therefore be necessary to safeguard our position and alleviate potential bottlenecks, for which similar monitoring mechanisms as will be developed in the Chips Act could be employed.

Governments can play an important role in stimulating market growth and bridging market gaps, as well as creating a fertile playing field for European quantum hardware and software providers to grow. Additionally, regulation such as foreign direct investment screening can help preventing (hostile) foreign acquisitions of critical technology manufacturers in the EU.

2.2.H: Objectives and recommendations

The following objectives have been identified:

→ Objectives by 2023 - 2026

- Establish fabrication processes and demonstrate performance from quantum devices fabricated in industrial-grade facilities which is comparable to state-of-the-art from specialised (e.g.) university clean rooms. These facilities should allow for scaling of volume or provide a clear path to scaling within the EU, to allow for an EU-based quantum fabrication ecosystem.
- Improve the yield and uniformity of quantum devices and ensure their functional performance, outlined in a clear roadmap, by using suitable fabrication and test processes in (if possible) established fabrication facilities.
- Improve access to, and streamlining of, fabrication and packaging facilities. Consider leveraging existing pilot line investments and workflows.
- Develop control calibration methods for non-trivial pulse shapes.
- Analytical design of control schemes and development of efficient descriptions thereof in order to facilitate both analytical and numerical design and improvements.
- Convergence of numerical optimal control and experimentation in many platforms, including handling of calibration uncertainties and other experimental constraints.
- Harmonized and standardized methods and protocols for qubit characterization, and QPU performance evaluation.
- Define and improve critical performance metrics and reduce the footprint of key enabling technologies in the electronic, cryogenic and photonic domain.
- Commercialisation of integrated electronic and photonic building blocks, including design, packaging and testing.
- Develop a proof of concept for large-scale, optimised and efficient cryogenic systems

→ Objectives by 2027 - 2030

- Demonstrate systems, manufactured at scale, which fully integrate quantum devices with a range of optical electronic components, including cryogenic-compatible packaging
- Implement reliable strategies for the control of mesoscopic systems, including complex control pulses and pulse shaping.
- Large-scale, high-power and accessible cryogenic system, potentially interfacing several cooling technologies, which can be integrated with classical infrastructure (e.g. datacentres).

Recommendations

- Setup the infrastructure for industrial-grade micro- and nano-fabrication facilities, providing the necessary resources for the manufacturing and packaging of quantum devices and components.
- Develop toolboxes that allow for the identification of performance limits for a given device implementation, and provide the protocols for realising optimal device and gate operations.
- Accelerate the development of critical European enabling technologies for quantum computing, quantum simulation, and quantum communications. Examples are: integrated electronics and photonics (devices, circuits and systems), high-performance FPGAs, high-end lasers, micro- and nano-technologies enabling cryogenic temperature operations, miniaturized packaging, cryogenic and vacuum systems.
- Foster the creation and growth of critical component manufacturers within the EU, while striving towards security of supply for non-EU components. Strive towards a robust supply chain for quantum technology within the EU and have the mechanisms in place to proactively monitor important changes over time.

1 quantum-technology-monitor-april-2023.pdf (mckinsey.com)

2.3

Education & Workforce Development

2.3.A: Impact, Societal Challenges and Quantum Opportunities

It is foreseeable that in the coming decades, quantum technologies will grow into a significant economic factor with considerable added value in the high-tech sector and a growing number of applied industries, that will address key societal demands and challenges, particularly in promoting a technologically soverign Europe. With this perspective, a considerable number of new jobs will be created in the QT sector, providing career opportunities for appropriately qualified individuals. Some papers show that an exponential growth of jobs is expected. Hence, it is fundamental to have workforce ready for the current market, as well for the future.

In order to uphold Europe's leading role in the realm of quantum technologies, it is imperative to proactively address the projected shifts in the labour market. A shortage of qualified professionals could potentially undermine Europe's competitiveness and technological sovereignty, thereby impeding technological and industrial progress. The impact of this skilled worker shortage is already discernible across various high-tech sectors, manifesting in tangible effects on growth rates. The nascent nature of quantum technologies with an emerging understanding of the possible industry use cases and monetization schemes further intensifies this situation. While parts of the industrial sector currently embrace and experiment with quantum technologies, the ultimate industry opportunities and training needs will have to be developed in a close coordination between all relevant stakeholders. The forthcoming available quantum workforce will therefore rely crucially on the training initiatives currently underway and those planned for the near future.

At universities, multidisciplinary programs at undergraduate levels will make a fundamental difference, allowing students from different disciplines to access quantum subjects and programmes. In academia, around 40 **specialised master's programs on "quantum technologies" and "quantum engineering"** currently exist or are being created across Europe. These measures should be supported and promoted by the EU, particularly in synchronizing and coordinating national programmes and efforts for creating a pan-European education and workforce strategy that enables compatibility, synergy and mobility throughout Europe. However, a simple estimate of the orders of magnitude illustrates that the number of graduates from these programs will be far from sufficient to meet the industry's demand for skilled personnel.

Therefore, **upskilling programs** for the qualification of employees who are already working in the industry must also emerge on a large scale. This is facilitated by the fact that many industry employees currently working in R&D already had exposure to research topics in the field of quantum physics during their time as university Ph. D. students. This already existing knowledge can be revived, updated and potentially proliferated within the organisation relatively easily through suitable training measures.

Moreover, there is also a huge number of professionals that, either by their role in the companies or the specific products they work on, will need to start from a very fundamental, not even technical, level to acquire awareness and skills in the quantum technologies field. A differentiation must also be done between vendors, where the technology is being developed and commercialised, and end users, where the technology is going to be deployed.

The knowledge of quantum phenomena and their technological possibilities is not only necessary in those disciplines that traditionally have quantum physics as part of the curriculum (e.g., physics). The application of quantum physics in technological contexts requires that new audiences also be trained to use quantum technologies, both in undergraduate and lifelong learning programs. This applies in particular to engineering ("quantum engineers") as well as to information and mathematics sciences and other natural sciences such as chemistry or the life sciences. In order to be active in the development of QT products and solutions, they need in-depth knowledge from the field of quantum physics, which can be taught both in academic and in upskilling programs. The fields in which a knowledge of quantum technologies are useful include application domains such as the chemical and pharmaceutical industries, transportation, manufacturing and logistics, finance and insurances, ICT (telecom, security), HPC and software, energy and utilities, consulting and services providers, aerospace and defence.

It is not only technically skilled workers who are needed in these industries. A well-functioning value chain in quantum technologies requires **well-trained personnel in other stakeholder groups** such as project and product and innovation managers, CXO's, business analysts, marketing and sales, and human resources. These stakeholder groups need a different kind of knowledge (in content and depth) than employees working in R & D. A first indication of the different kinds of knowledge and skills structure desired by industry has been provided by the "Qualification Profiles for Quantum Technologies" developed by the QTEdu CSA in 2022. They provide examples of the competences an individual has acquired through education or further training in preparation for employment in industry. The industry needs analysis carried out within the QuCATS CSA and the QTIndu project further specify the human resource requirements of industry, enabling community-driven training efforts to meet these needs.

A significant barrier to sustaining Europe's efforts in QT development can come from a lack of engagement and enthusiasm from society, which is crucial for support for i.a. i) continuing public funding of fundamental and applied research in the area, ii) a steadily growing recruitment to early stages of the workforce development pipeline and iii) public acceptance of the emerging application domains and products while navigating ethical, financial and globally strategic considerations. Previous technological developments, such as Nuclear Sciences and Artificial Intelligence, have suffered from public backlash, in the absence of a broad coordinated approach to these issues. The most effective means to acceptance is generating widespread awareness and "quantum literacy", such that the public understand sufficient basics of QT to be informed without generating hype, fear or and misconceptions. **Europe must urgently expand efforts in QT outreach**, particularly as technology is rapidly reaching realisation.

While Master's and industry training programs supply the immediate workforce need, in the long-term the QT workforce will be composed of those who are just now entering school level education, and it is essential that these students are provided with the opportunity to set themselves on the path towards the Quantum industry. Doing so requires exposure to QT in their schooling such that they are inspired to work towards a career in this field, yet research in the QT Education community has found that currently there are many countries with little or no QT included in national curricula. This is a significant missed opportunity in reaching the future quantum workforce from an early age, and should be addressed via international coordination. Bringing awareness of these emerging technologies to teachers and schools is crucial to position Europe as the leader in the field.

To coordinate many of these Quantum Flagship efforts across the workforce development pipeline, the **European Quantum Readiness**

Center (EQRC) was recently formed. Efforts are divided in three strands. In EQRC-resources, quantum playlists of online videos as well as open source education and training modules will be hosted. These efforts will need to be coordinated with other stakeholders who are aware and/or produce educational resources Each of these will be mapped to the sub-items of the European **Competence Framework for Quantum Technologies**, which is foreseen to be the **universal language for knowledge and skills throughout the training pipeline**. In EQRC-analysis, industry needs will be continually assessed both qualitatively (through broad stakeholder interviews) and quantitatively (through comprehensive analysis of job posts and other online accessible data sources) as the industry matures. This provides both a continuously updated overview of the depth and breadth of activities in the quantum industry and enables adjustments and updates to the competence framework to ensure that all education and training providers may align to the evolving industry needs. In EQRC-adoption, all stakeholders in the education and training ecosystem obtain up-to-date information about best practices and may be incentivized to follow these by submitting an Accord describing their Quantum Readiness efforts and obtaining public recognition for this.

2.3.B: R&I challenges, strategy & roadmaps

As more and more companies successfully incorporate Quantum Technology into their value chain, the need of a ready quantum workforce increases. Early growth in the potentially disruptive parts of quantum technology is driven by first movers and early adopters establishing efforts to increase their quantum technology readiness level.

2.3.B.1 Monitoring the workforce needs of industry

One particular challenge is that the pace at which the industry is currently developing requires skilled technical profiles to be developed over a short timeframe. There is a need for dedicated routes charted for different stakeholders towards specific skill profiles, including those with many different levels of specialisation and knowledge, ranging from technology suppliers, researchers, developers, and end-users. As technology develops, the skillset demands of these profiles develop and change, and thus a continuous monitoring of industry needs and workforce demands is also required.

Recommendations

- Continuous tracking of the emergent workforce needs (short term)
- Analyse and continuously develop a wide range of skill profiles and clarify the match to targeted education and training programs. (short term)

2.3.B.2 Foster upskilling and workforce training efforts

To meet industry training needs, continuing education programs should be established for various stakeholder groups in the industry workforce as well as comprehensive support for on-the-job training. A special focus should be on target groups that traditionally had no contact with quantum physics in their studies. Overall, these upskilling programmes must be modular, flexible and adaptable in order to respond to changing requirements as technologies develop and mature, and new applications emerge.

As in other business sectors, these upskilling activities should in the long run not be based on public funding initiatives, but rather on a thriving training provider ecosystem consisting of e.g. in-company training, specialised training companies and professional development and executive training programmes hosted at higher education institutions. There should be programmes that actively help to shape the transition to commercialisation of QT training. The upskilling efforts should not only emphasize basic skill training but also imbue corporate decision makers with an updated understanding of the emerging possibilities from quantum research in order to support the development of most efficient corporate Quantum Readiness initiatives. In addition, it should be emphasised that such workforce development efforts succeed in a spirit of active collaboration between industry and academia to ensure joint definition of skill and knowledge requirements and offer joint knowledge transfer via secondments and training opportunities.

In addition, Europe has the potential to attract highly qualified specialists. However, immigration controls and export control regulations often prevent non-European specialists from working in Europe outside an academic setting. Given the size of the actual market, which is still a small niche, provisions for work visas generally do not yet list QT specialists, making it even harder to develop a thriving European ecosystem and workforce.

Recommendations

- Foster the emergence of a comprehensive platform of varied, high-quality, open-source training modules which can be recombined by commercial actors to suit specialised needs (short and medium term)
- Additional funding to create specialised training programs to educational providers outside academia (short and medium term)
- Foster the commercialisation of QT training by supporting programmes for QT training directed to different stakeholders from industry (medium)
- Matching companies wishing to reskill their staff with companies and training institutions that have the expertise (e.g. quantum computer manufacturers, training companies). (Short and medium term)
- Develop programmes for the training of QT workforce on a non-academic level (vocational training for technical staff) (long term)
- Develop programmes for corporate decision makers on quantum adoption strategy (short term)
- Putting in place national and European regulations to attract international talent to Europe (e.g., talent visas)

2.3.B.3 Foster academic QT programs beyond the traditional boundaries of QT

As mentioned, dozens of specialized Quantum Technology degrees are currently emerging. Highly qualified technical staff will form the backbone of the emerging quantum technology workforce. It is therefore crucial that these efforts i) are continually refined to provide state of the art quantum technology competences and ii) the number of graduates is increased significantly. The latter can be addressed by both increasing the number of such specialized technical programs as well as by continually decreasing the barrier of entry of non-physics candidates from technical fields like computer science, mathematics, engineering and chemistry. The former is often restricted by the availability of the wide range of specialised competencies needed at the particular university. Thus, ongoing efforts pursuing pan-European teaching synergies (such as shared/virtual courses and entire degrees) should be amplified. As specialised degrees such as quantum engineering are developed, it is crucial that they emerge as unique disciplines rather than extensions of classical engineering or physics degrees. Instead, quantum engineering should be recognised and nurtured as a stand-alone discipline, characterised by its unique models of abstraction that enable pragmatic engineering of quantum systems. The advent of quantum engineering promises to bridge existing gaps, offering fresh perspectives on a spectrum of topics. This spans from the intricate design and integration of components, to the optimisation and verification of their functionality. Furthermore, it is poised to introduce invaluable abstractions and heuristics that can redefine the quantum landscape. To support this educational transformation, the emerging open source ecosystem of specialist learning and assessment modules (EQRC-resources) should be continually expanded to comprehensively cover all Quantum Competencies and thus offer not just broadly accessible but also quality-controlled teaching supplements suitable to any Quantum Masters course. Given the increasingly interdisciplinary recruitment, it will be important to support the development of conceptual and intuitive approaches to quantum education. However, educational material alone is not sufficient, it must be accompanied by appropriate training for teaching staff, which may be accomplished by developing and implementing QT-upskilling workshops, aimed at academic staff in non-quantum fields, and hosted by the Quantum community. Furthermore, in order to ensure sufficient recruitment into these specialised degree programs it will also be crucial to introduce quantum technology concepts within the various broad bachelors – not to expand the curriculum but to offer exciting perspectives of the introductory concepts. In general, this major educational transformation will only be successful by constantly keeping the emerging industrial demands in the foreground. This alignment is foreseen through the continually updated Competence Framework but will also require a deliberate attention to concrete and comprehensive industrial representation in the planning and execution of these new study programs (e.g. by industry representation in advisory boards as well as industrial guest lecturing and supervision and comprehensive internship programs). In addition, acquiring hands-on experience can be a significant roadblock towards generating the skill profile required for industry. There is thus also a need for a substantial scaling-up of EU efforts in providing opportunities for hands-on experience outside of formal education programs. Finally it should be mentioned that a maturing Quantum Industry is also going to require a substantial workforce beyond the technical domains to support functions like, business development, sales, project management, strategy and investment and human resources. Thus, it is crucial that steps are taken to bring applied introductory quantum courses into the business schools. This can only be achieved in a timely manner by supporting at the early stage curriculum development experimentation before, but in anticipation of, the emergence of a large-scale business school graduate market within the quantum technology field. These cutting edge educational activities will not only be instrumental in nurturing talent but also form a basis for attracting substantial talent on the global educational marketplace. If Europe is to maintain a position of Brain-Gain rather than Brain-Drain, it must be offering globally attractive education opportunities. As such, emphasis should also be to collectively alleviate crucial logistic factors such as visa expedience and flexibility for incoming talent.

Recommendations

- Foster the development of an ecosystem of academic institutions with QT master programs to exchange best practices, build networks and develop common learning opportunities (short and medium term)
- Development of an open source ecosystem of learning and assessment modules enabling recombination to suit diverse stakeholder training needs. (short term)
- Development and implementation of a series of QT-upskilling workshops for teaching staff in non-quantum fields. (short term)
- Access to the comprehensive Quantum Flagship internship program for non-specialist students. (long term)
- Establish a Quantum Flagship coordinated internship program offering short and long term internships in partner organisations of all future Quantum Flagship projects and within the European quantum technology industry. (long term)
- Foster the exchange with other relevant key capacity areas (HPC, AI) (long term)
- Expansion of quantum technology education to business schools.

In addition it is recommended that:

- The submission of a Quantum Readiness Accord is considered as a key performance indicator for all future and ongoing Quantum Flagship projects and European and nationally funding commercial start-up support.
- The Competence Framework is disseminated and adopted widely within EU education programs, including national efforts beyond the Flagship.
- The community develop and continually update qualification profiles for jobs specific to industry roles ranging from the supplier to the end-user, accompanied with training and certification material to reach them via a number of educational tracks.

2.3.B.4 Outreach and quantum awareness among the public, government, and industry

Awareness of Quantum Technologies is a key underpinning of future work in education and training. First, because inspiration is the seed from which the future quantum workforce is recruited. Second, because those citizens who are or will become policymakers, start-ups or companies professionals, or public officers, must know of the implications of QTs in order that they are considered in decision-making processes, rather than considering them to be a far-off concept with no real applications. And third, because acceptance of the new technologies in society critically depends on increasing accessibility of the topic to a broad audience.

Regarding inspiration, high school education remains a missed opportunity for developing the fascination with the field required to set students on a career path to the Quantum workforce. In many countries, quantum technology does not enter national curricula, or is available only to select few students who pursue rather specialised fields of study where they are prepared for university studies. It is thus essential that quantum technologies, not only historical aspects of quantum physics, reach all secondary students - not only those in specific countries or on specific education paths. One means by which this may be achieved is through community-developed resources, which may be generated by technical projects as part of their communication & dissemination requirements. Within the Qucats CSA, model curricula and best practice recommendations for teaching Quantum Technologies in high schools will be developed, supported by the Competence framework as a common language for communicating learning outcomes. These curricula could act as a blueprint for implementing QT into high schools in the member states. Addressing teachers and other education professional to bring awareness of the emerging field of quantum technologies is crucial to develop early interest in students.

Outreach and dissemination of quantum technologies to the general public is key. One major recommendation is that QT Education and Training be further integrated into the operation of all Quantum Flagship projects. It should be considered a core part of project dissemination. We therefore recommend that:

Recommendations

- 2025 is dedicated as an international year of Quantum science and technology.
- All future quantum flagship projects are required to participate in regular dissemination and communication of their results to the public on World Quantum Day (annually April 14th).
- This will demonstrate the cutting edge of applications and use cases of technology, embedding them into public awareness. (long term)
- All future quantum flagship projects are required to generate resources which explain their work and its implications to the level of high school students, collected and curated on an EU coordinated platform. (long term)
- A common coordination platform is set up which connects outreach activities from different projects, creating an outreach ecosystem (long term)
- Programs are set up to develop and evaluate QT teaching materials for high schools (short term)
- Flagship coordination should work with the quantum technologies community to pursue a consistent and inspiring message with media organisations to ensure public awareness and understanding develops in parallel with the technology.

2.3.B.5 Foster quantum use case awareness and adoption for industry growth

As more and more companies successfully incorporate Quantum Technology into their value chain, of course the needed quantum workforce expands. Early growth in the potentially disruptive parts of quantum technology are driven by first movers and early adopters establishing efforts to increase their quantum technology readiness level. However, a crucial determinant for the quantum industry growth curve is the speed at which awareness of these quantum-driven and enhanced monetization pathways diffuses throughout the relevant industries. Therefore, as successful quantum product and service use cases emerge it will be crucial to develop transparent, research-driven guidelines and decision-maker training on how best to assess, value, and adopt quantum technologies to ensure that every organisation ramps up their quantum readiness and exploitation efforts when they generate most long-term value. A crucial component that should not be underestimated here, is the value in understanding and acknowledging the crucial role for the maturation of the industry ecosystem and supply chain played by early-stage corporate adopters before the technological potential and the value chains are fully explored.

Recommendations

- Establishment of academic-industry partnerships to develop guidelines and educational resources for industry training around quantum technology adoption strategies. (short term)
- Development of a standardised stakeholder and domain specific set of quantum adoption levels and best practice guidelines which may be used by companies to assess their current level of readiness and plan accordingly. (shorter term)

2.3.C: Objectives and recommendations

Realising the recommendations described above requires continual alignment with ongoing Flagship bodies and initiatives such as the QTEdu community, the Educational Quantum Community Network for inpur on national educational agendas and QuIC for special workforce demands in the industry. In addition it requires the continual expansion of the following infrastructures:

- The creation and maintenance of a fully developed language of quantum technology skills applicable at all level of the workforce development pipeline, with a regular updates via a feedback mechanism (Quantum Technology Competence Framework, below left)

And, coordinated by the European Quantum Readiness Center (EQRC):

- An open source ecosystem of learning and assessment modules enabling recombination to suit diverse stakeholder training needs (EQRC-resources)
- Continuous qualitative and quantitative tracking of the emergent workforce needs (EQRC-analysis)
- Widely adopted incentive scheme to acknowledge the quantum readiness efforts of all stakeholder organisations along a set of continually updated best practice guidelines (EQRC-Accord, below right). Since the effectiveness of positive reinforcement through public prizes and acknowledgement has been thoroughly documented in both topical domain and for cross cutting issues such as Diversity, Equity and Inclusion, (eg with the Athena Swan program), it is recommended that the Accord program is expanded and given growing visibility and prestige in the coming decade.
- Deployment of training courses for teachers of final year courses and other educators to spark interest in quantum science
- Link companies seeking to reskill their staff with companies offering appropriate expertise.

Figure 2.3.1: Key areas of skill and knowledge for quantum technologies. The figure is from the European Competence Framework for Quantum Technology

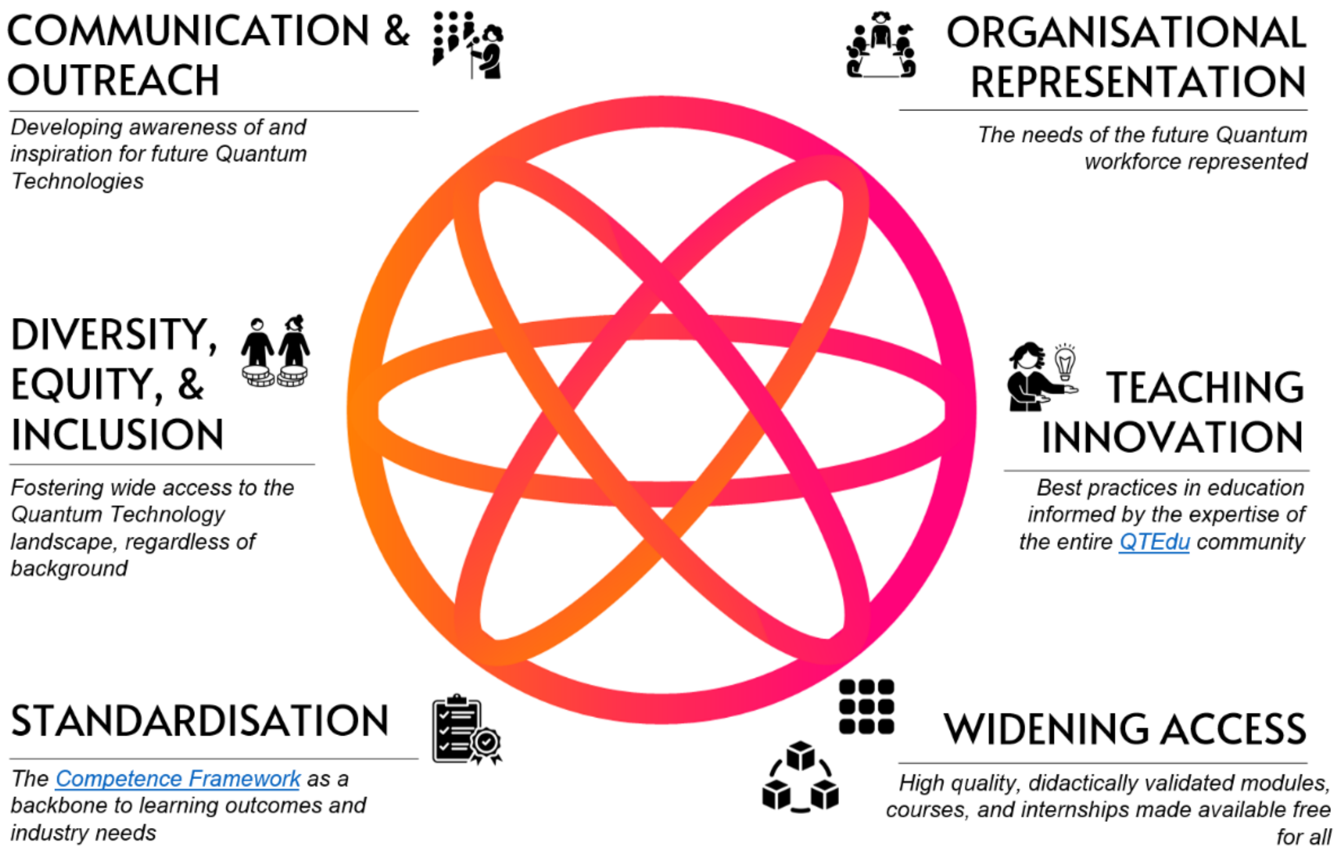

Figure 2.3.2: Candidates for main pillars of organizational contributions within work force education and upskilling in quantum technologies.

https://www.frontiersin.org/articles/10.3389/frqst.2023.1225733/full

These infrastructures are currently fully supported by public funding. This will also have to continue in the near term. However, in the medium to long term such infrastructures should be developed into public-private partnerships in order to ensure the long term sustainability of these efforts.
To ensure the robustness and relevance of the initiatives and recommendations mentioned above, it is vital that European workforce development initiatives are continually aligned with and mutually inform national efforts within Europe. Moreover, they should be inspired by and remain adaptive to ongoing and emerging global efforts in the quantum technology sector. (See section 2.7 for international cooperation considerations.) In addition, to foster innovation and ensure a comprehensive talent pool, it is imperative to prioritise diversity and inclusion in all quantum technology education and workforce development initiatives such as overcoming the gender gap in recruitment. Embracing diverse perspectives and backgrounds will not only enrich our quantum community but also drive more innovative solutions in the sector. (See section 2.8 for recommended efforts.) Finally, it is crucial that all education and workforce development efforts be planned in close alignment with the national and European coordination and assessment efforts within R&D as well industrial use case and ecosystem development in order to ensure that workforce estimates are always based on the most accurate technology roadmaps and industry growth forecasts.

→ Objectives by 2023 - 2026

- Define the competence baseline and assess industry needs, including skill profiles required for specific jobs ranging from supplier to end users.
- Raise awareness for different business sector use cases in QT i) education, ii) training and iii) corporate and policy maker decision making.
- Summarise best practices and established resources of first mover organisations designing and implementing QT Master programmes to expand these efforts across Europe including a continual focus on expanding entry points from miscellaneous disciplines.
- Foster the creation of a pan-European ecosystem of mutually cooperating academic institutions active in the field of QT Education, and set up an incentive structure for cooperation.
- Raise QT awareness and acceptance at all academic levels and in the general population throughout Europe.
- The existence of a comprehensive open educational ecosystem of modular components to be built into courses for outreach, high school, university, and industry training, continually updated to address industry and societal needs via an adopted incentive structure.
- Establish a European certification scheme for quantum technology training to ensure comparability of European certificates.
- Align higher education QT learning objectives with industry training and hiring criteria through the Competence Framework, allowing for a continuous adjustment and revaluation of curricula required

→ Objectives by 2027 - 2030

- Establish a European Framework Partnership Agreement on Quantum Technology Education, addressing QT education through the development of dedicated education programs from high school to industry training in each EU member, with individual national projects coordinated by the FPA. This will serve as a coordination platform for future national QT Education projects.
- Inclusion of QT within >80% of high school curricula across Europe.
- 500+ institutions adopting the Quantum Readiness Accord as an evaluation and dissemination tool for innovations in the field of Quantum Education and Workforce Development.
- Adoption of the Quantum Readiness Accord considered as a criterion for national institutional evaluations.
- Widespread adoption of the Competence Framework by > 80% of Quantum Technology Master programs and industry training programs across Europe.
- Establish Quantum Flagship coordinated internship program to be maintained by future Quantum Flagship projects.

Recommendations

- Upskilling: Set up programs for QT training and adoption strategies directed to different stakeholders from industry (short and medium term)
- Upskilling: Foster the commercialisation of QT training by supporting programs for in-company training, specialised training companies and professional development and executive training programmes hosted at higher education institutions (medium term)
- Upskilling: Develop programs for the training of QT workforce on a non-academic level (vocational training for technical staff) (long term)
- Academic/Upskilling: A comprehensive pan-European internship program should be embedded throughout all future Quantum Flagship projects, offering a direct route to QT competences. (short and long term)
- Academic: Generate a coordination platform for QT master programs to exchange best practices, build networks, promote international exchange of talent, and develop common learning opportunities (short and medium term)
- Academic: Develop of an open source ecosystem of learning and assessment modules enabling recombination to suit diverse stakeholder training needs. (short term)
- Outreach: Outreach and awareness materials aimed at the general public and high school, should be generated by Quantum Flagship projects. Regular public outreach events held by Quantum Flagship projects as a routine part of their communication activities, annually held around World Quantum Day. (short and long term)
- Outreach: Setup a coordination platform to connect outreach activities from different projects, creating an outreach ecosystem (medium term)

Recommendations

- Outreach: Setup programmes to develop and evaluate QT teaching materials for high schools (medium term)
- Adoption: Establish the submission of the Quantum Readiness Accord as a key performance indicator for future Quantum Flagship projects and European and nationally funding commercial start-up support, ensuring adoption of best practices for QT Education and industrial Quantum Readiness (medium and long term)
- Adoption: Establish the Competence Framework for Quantum Technologies as a common language for qualifications, skills, and training needs (medium and long term).

2.4

Standardisation and benchmarking

2.4.A: Standardisation

The standardisation of quantum technologies can help to structure and accelerate market uptake by providing reliability, consistency, and interoperability with existing infrastructure, systems and components. Standardisation not only concerns the requirements that form the basis of certification, but also addresses vocabulary, terminology, quality benchmarks, models, exchange protocols, and many more topics. In light of the strong influence exercised by other countries on the international standardisation bodies, it is imperative that Europe takes a proactive approach to the development of standards and benchmarks, lest it finds itself forced to adapt to foreign countries standards, which may penalise European technology. Furthermore, development of standards on the European level facilitates to create a federated and strong European voice on the international standardization level, as compared to finding initial consensus as (EU) national states with less weight in international SDOs. Compared to the international level, strong consensus can be found quicker in the European Economic Area, building on strong societal, cultural, scientific and economic bounds between the countries of the EU. The impartial and reliable comparison of different quantum technologies necessary to give users the tools to evaluate quantum solutions requires the definition and design of a set of benchmarks. Benchmarks are useful for assessing progress, performance and capability to solve a problem. In a recent survey, [1] as shown in the following graph, standardised benchmarks, metrics & measurements are the strongest request from industry and academia.

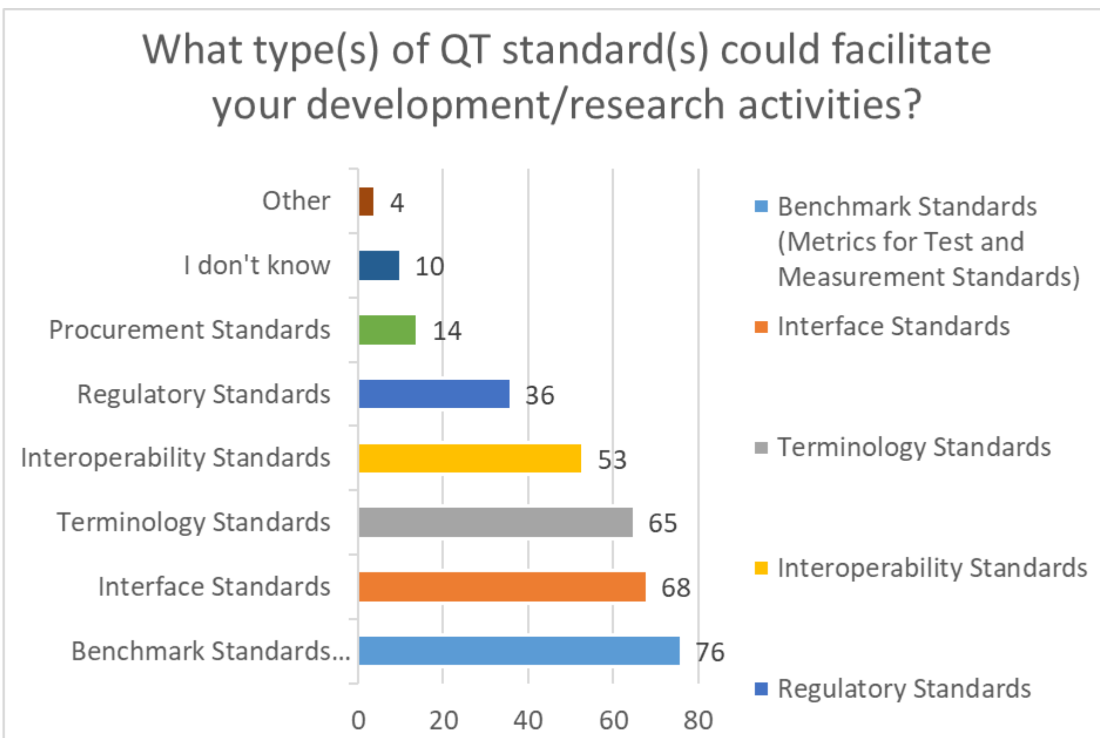

Figure 2.4.1: Request from academia and enterprises for standardisation (Survey 2023 QuCats)

[1] Survey made by the the CSA QuCats in the European Quantum Flagship (Not yet published)

Again the answer to the question at what is the most important standardisation activity for your organisation, is having the proper measurement facilities for benchmarking and conformity to standards and regulation.

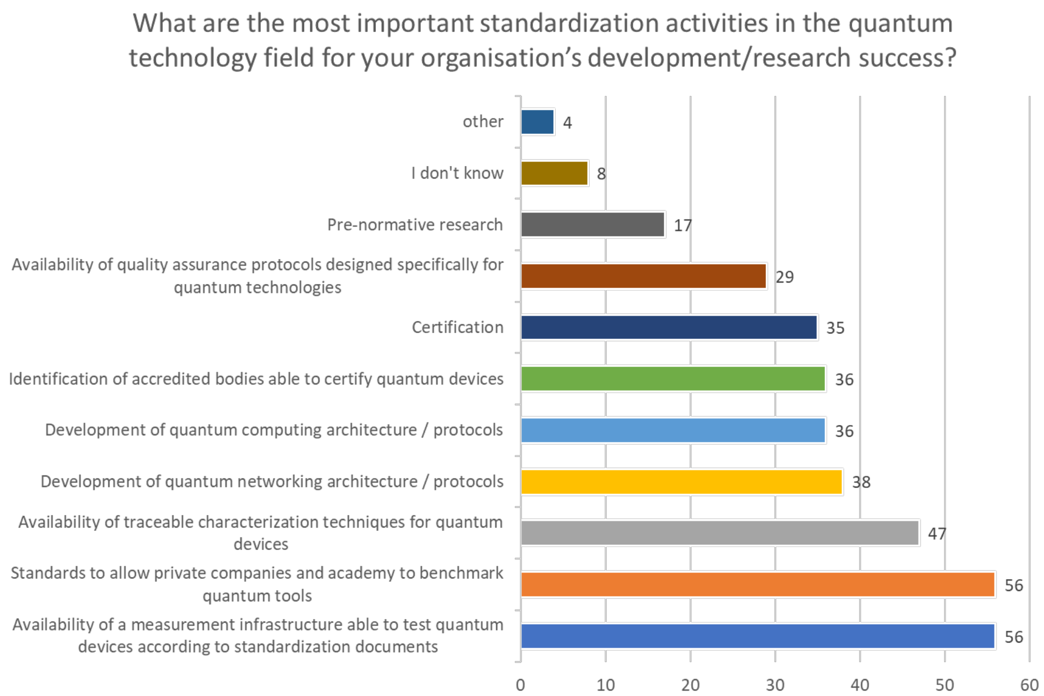

Figure 2.4.2: What are the most important activities for your organisation development/research success

The results of this survey demonstrates how the quantum ecosystem in Europe and the USA understands how important standardisation is and what is useful for the fast moving landscape of QT and should be available as soon as possible. Measurement infrastructure is one of the most requested activities, these are being developed within the EU project Qu-Test that develops federated test beds for QT.

To answer to those needs, the European standardisation agencies CEN and CENELEC established on March 2023 a new joint committee, JTC22, on quantum technologies. This new committee is the based on previous work of the Focus Group on Quantum Technologies (FGQT) mandated by CEN and CENELEC, which delivered beginning of 2023 a Roadmap on quantum-technology standardisation in Europe.

With its Standardisation roadmap, the FGQT is the first group worldwide to identify standardisation needs for all aspects of QT. The main objective of the Roadmap is to give a comprehensive and relational classification of QT, and to underline the interdependence of ongoing and prospective standardisation efforts in this field. Specific standardisation needs have been identified to the best extent, given the present state of knowledge from both user and provider side. Due to the dynamic state of QT, relevant parts will be added to standardisation efforts in the future. Naturally, the roadmap

needs to be an open document, evolving with the progress of technological development, as well as with the progress in QT standardisation itself.
JTC22 will be responsible for standardisation in the field of quantum technologies including quantum enabling technologies, quantum sub-systems, quantum platforms & systems, quantum composite systems as well as quantum applications covering the following areas:

- Quantum metrology, sensing and enhanced imaging
- Quantum computing and simulation
- Quantum communication and cryptography

The new committee is organized in four working groups [2] (final decision pending); one on strategy and three accordingly to the domains above. Members of these working groups are experts from quantum technology manufacturers and academia from all over Europe[3]. Part of the initial work programme will also include identification and possible adoption of relevant international standards such as ISO/IEC JTC 1 and other technology committees at ISO, IEC or ITU-T. At the same time, output and content from JTC22 will be available to represent the European consensus in international SDOs. JTC22 will further work in a coordinated way with ETSI and connect to already existing standards. Thus, European market needs will be represented, as well as underpinning EU legislation and policies. Where relevant, the work programme will include the development of CEN and CENELEC deliverables that address European needs and requirements.

Meanwhile several National Standardisation Bodies (NSB) established mirror committees to JTC22. They are in charge of evaluating the documents proposed by JTC22 and other international standardisation organisation and to participate with their experts to the committees as JTC22 in Europe but also to all the others in the world. Indeed the JTC1 of ISO-IEC (joint committee for digital technologies) has already established a working group (WG14) on quantum computing and some other standardisation organisations such as IEEE have also began to work on quantum technologies. Presently, there is a UK proposal to establish a new joint committee in ISO-IEC on all quantum technologies, in which Europe should make sure representation of the consensus found in FGQT, JTC22 and ETSI is present. Ideally, ideas from the FGQT roadmap will shape the organisation of new TCs on an international level and thus help to effectively connect EU standardisation to the international level in both ways (CEN/CENELEC <-> ISO). The aforementioned, publicly available Roadmap of FGQT can serve as a (first-of-its-kind) blueprint for a coherent standardisation framework, put forward by European experts on the international level, as for instance in the road mapping initiatives currently under way at IEC.

Indeed, it is important for the EU QT ecosystem that experts from all interested parties, from manufacturers - including start-ups and small innovators - to end users - including academia and European programs as EuroHPC and EuroQCI - and purchasers, are able to participate with enough resources for providing thorough work in the different committees. **The main challenge for the following years is having enough experts in the mirror committees in NSB from manufacturers, potential users and academia to join the groups and participate to the different standardisation propositions in the main European and international organisations, in particular CEN-CENELEC JTC22.**

Recommendations

- Set up adequate incentives to stimulate the participation of industry and academic representatives and quantum experts (from both industry and science) in JTC22 and potentially other relevant SDOs to actively develop standards. Encourage EuroHPC and EuroQCI grantees to actively participate and contribute to JTC22 standards developments
- Request and support JTC22-Strategy group to develop an interactive and easy-to-navigate living document on existing and upcoming standards *and up-to-date information on global standardisation activities* that affect the quantum ecosystem.
- Prevent multiple coordination of QT standardisation at European level by mandating the JTC22 strategy group. Stimulate participating other standardisation activities to contribute to JTC22 strategy group.

2.4.B: Benchmarks

A benchmark is an accepted reference providing an objective measure by which others may evaluate performances and capabilities of the device under test, which would stimulate collaboration, competition and investment in QT.

Benchmarks for quantum computing and simulation, quantum sensing or quantum communication, are genuine measurement tools that require research and development for their elaboration. Benchmarking is intended to support the whole technology value chains: technology development, use case development, research and innovation programme monitoring, market creation and structuring, regulation, public procurement...

Furthermore the particular need for QT benchmarks arises from the emerging character of the field, with many diverse technologies being explored, yielding a need for reliable and independent testing and assessing them. It also comes from the high promises of breakthrough for a wide range of quantum applications, and the strong international competition pushing the actors to claim the best performance without common understanding. Hence, objective and reliable benchmarks should be designed. In the particular field of quantum computing and simulation, the challenges to achieve comparable measurements come from the diversity of the hardware platforms, their specifications in terms of physical properties and applications, their still low readiness, and the potential rapid evolution of the technologies. Hence, benchmarks should evolve in accordance with the technology.

Currently, benchmarks are considered at different levels with complementary approaches. At the hardware component level, they concern the characterisation of fundamental physical properties and draw particular attention from the device manufacturers. Nevertheless, some performance and capability evaluation of a technology can also be performed at the system level by considering the system as a whole. Performance and capability can also be measured at an even higher level by considering applications only, at the so-called application-level. This approach is of particular interest for end users, as it allows for the assessment of any practical quantum advantage.

Regarding quantum computing and simulation, several initiatives have been launched at the international level: IBM (Quantum Volume, CLOPS...), Super.tech (SupermarQ), QED-C, US DARPA, US DOE (Sandia National Labs., etc), UC Berkeley...

In Europe, several initiatives, mainly oriented to applications, started in several countries, while the Horizon Europe Qu-Test project gathers RTOs and National Metrology Institutes harnessing harmonized characterisation and testing of quantum components and subsystems. The below table gives an overview of the current benchmarking initiatives on quantum computing in Europe.

Origin	Germany
Benchmarks	BenchQC
Basis	- Quantum machine learning, Physics simulation, combinatorial optimization - Evaluation of both the classical and quantum parts of the computing.
Consortium	BMW Group, ML Reply, Optware Quantinum, Fraunhofer Inst. (IKS, IIS)
Origin	France
Benchmarks	BACQ
Basis	- Optimization, linear system solving, quantum physics simulation, prime factorization, including QScore methodology and others. - Aggregation and analysis of multiple metrics (computational and energetic)
Consortium	LNE, Thales, CEA, CNRS, EVIDEN (ATOS), Teratec
Origin	The Netherlands
Benchmarks	TNO project
Basis	Q-Score methodology extension (hardware and applications)
Consortium	TNO
Origin	The Netherlands
Benchmarks	QPack
Basis	Quantum Approximate Optimization Algorithm (QAOA) and Variational quantum eigensolver (VQE).Aggregation of multiple metrics.
Consortium	TUDelft
Origin	EVIDEN
Benchmarks	Q-Score
Basis	Single score for the effectiveness of solving standard problems (MAXCUT optimization problem to start).
Consortium	EVIDEN (ATOS)
Origin	Europe
Benchmarks	Qu-Test
Basis	- European project (Horizon Europe FPA and SGA 2023-2026) for supporting open testing and experimentation for quantum technologies in Europe. - Establishing measurement capabilities for characterization and testing of systems, sub-systems and components, consisting of a Quantum computing testbed, a Quantum communication testbed, and a Quantum sensing testbed. - Developing harmonized measurement protocols for agreed key characteristics.
Consortium	12 RTOs and National Metrology Institutes from NL, FI, BE, DE, AT, FR, IT and 12 industrial companies.

Table: Current European initiatives on quantum computing benchmarking (non-exhaustive). Additional efforts are dedicated to the subject in various contexts (FZ Jülich, QuIC...)

So far, all the application-oriented benchmarking initiatives are national but there is a strong willingness from all projects to work together for complementarity and to prevent double effort.

Recommendations

- To encourage to have a single coordination forum between the different European benchmarking initiatives
- Encourage exchange between standardisation and benchmarking activities
- Define a programme at European level to support R&D effort with cross-disciplinary approach and inclusion of academia and industry for benchmarking.
- Support access to the machines through EuroHPC for benchmark development and testing to enable the development of quantitative and objective benchmarks.

2.5

Funding: private & public

2.5.A: Private Funding

Quantum technologies are considered strategic technologies by European Union (EU) institutions. The success of EU start-ups and scaleups, who aim to become the EU equivalent of today's tech giants, depends on their timely access to capital. Quantum technologies are foundational, and are likely to become platforms that enable future scientific advances, from the discovery of new materials to novel molecules, and spur technological developments across multiple industries. Financial resources are the lifeblood of deeptech companies that seek to turn scientific excellence into industrial leadership. The EU together with several of its member states, like other governments across the globe, has started to set up funding mechanisms to support local quantum companies. Unfortunately, European private investors have not yet followed suit.

According to a recent report by McKinsey & Company[1], the EU is today home to roughly 25% of global startups and SMEs in the quantum-technology sector, on par with the United States. However, EU companies attracts only 5% of private investments in the sector, ten times less than similar companies in the United States. Private US investors lead investments into quantum technologies globally outstripping EU private investment by a factor of 5.4x. The difference is not merely due to the size of funds and expertise of quantum technologies but an investor culture that is inherently risk averse to support the competitive expansion of the Union's commercial quantum technology market. None of the top five biggest investment deals of the decade were in EU companies, Four of these deals closed in 2022, two of them in SPACs: SandboxAQ (US, $500 million), Rigetti (US, $345 million), D-Wave (CA, $300 million), and Origin Quantum (CN, $149 million)

The EU, together with several of Member States (MS), has set up funding mechanisms to support local quantum companies, notably through the European Investment Bank (EIB), European Innovation Council (EIC), and the European Investment Fund (EIF). These mechanisms play a vital role to derisk private investment and attract new capital. However, neither the scale nor speed of deployment of the funds are proving fit for the realities of competing in the global quantum arena . One of the results is that in 2022 the valuation of EU start-ups was a paltry 30% of American ones, and the funds deployed in EU start-ups were just 50% that of their American counterparts[2]. EU quantum companies are, in effect, being placed at a significant disadvantage relative to their competitors in other regions of the world, including the United States, Canada, the United Kingdom (UK) and China.

The challenging financial situation for EU quantum companies is exacerbated by the present economic downturn weighing on valuations of nascent tech companies[3]. Venture Capital funding of start-ups has plunged by more than 50% in the past 12 months. This scarcity of capital could lead to an "extinction event" for the EU's quantum scaleups, where companies holding collectively hundreds of patents on innovative intellectual property (IP) are unable to close funding rounds and are either abandoned or sold to foreign competitors at several discounted prices.

Urgent and determined actions can reverse the trends and allow EU companies to remain top competitors in the global race of quantum commercialization.

Recommendations

- Raise the upper limit on direct equity investment from € 15 million to at least € 75 million in order to mobilise adequately sized co-investments for growth funding rounds (€ 100 - € 250 million) and anchor European companies and talents in Europe, rather than seeing them migrate their activities abroad. The European Tech Champions Initiative (ETCI) can serve as a blueprint for this undertaking[4].
- Enable the EIB / EIC or other European-financed investment fund to take a 'lead investor' role, namely to set the financial terms of funding rounds and the composition of the company Board. Such a measure has been successfully implemented by the Business Development Bank of Canada[5].
- Alternatively to the previous recommended action, the EIB / EIC should deploy their capital in rounds led by existing private investors in the companies ("legacy" investors). Such a "large follower" has been used by several foreign-government funding bodies, such as the UK's National Security Strategic Investment Fund in the recent investment rounds of Quantum Motion and Riverlane. In Riverlane's case, one of these legacy investors is Amadeus Capital, co-founded by EIC Board Member, Hermann Hauser.
- Simplify and accelerate the due diligence process of the EIC / EIB to be more in line with common practices from private capital investments (on the order of 4 - 6 months).
- Advocate best practices (do's and don'ts) for public procurement programmes and their implementation within the EU, including at national member state level. As a notable example, public procurement programmes should refrain from demanding the exclusive ownership of intellectual property developed in the course of manufacturing and delivering the agreed goods / service.
- Allow and encourage national and European pension funds to invest in European quantum companies, thereby offering European citizens a slice of the benefits of Europe's growing quantum industry. Such pension-fund participation in tech private equity has proved successful in Canada and is now starting up in the UK[6]. At present, less than 0.018% of the more than $3 trillion in total assets of European pension funds are allocated to European ventures[7].
- Pursue a measured implementation of the recent foreign direct investment screening (Regulation No 2019/452) such that European quantum companies remain attractive targets for European and foreign investors alike, while maintaining Europe's strategic capability in the field. The balanced approach concerns both venture-capital investments as well as future mergers and acquisitions.
- Support the education of investors in the investment opportunities presented by quantum technologies and the EU quantum commercial ecosystem in particular.
- Provide reliable and beneficial legal and financial frameworks for private investments.
- Promote the creation of initial public offering opportunities for large EU quantum companies with leading providers of EU stock exchanges, such as Euronext.
- Support existing and new quantum-focused accelerators, and promote connections between them to create a multi-hub accelerator programme across the EU.
- Support IP generation and protection (see later) as a cornerstone of new firm creation.

[1] The Quantum Technology Monitor, McKinsey & Company, April 2023
[2] Pitchbook deal table, completed deals, 2000-2022.
[3] Financial Times, Venture Capital Investment, April 5th, 2023
[4] European Tech Champions Initiative
[5] Business Development Bank of Canada (BDC) has served as Lead Investor in 35% of its investments
[6] The Economist: "British pension funds agree to invest more in private markets"
[7] The State of European Tech 2021
[8] McKinsey&Company Quantum Technology Monitor 2023

Europe has a once-in-many-generation opportunity to set itself as a global leader of a transformative technology. The EU has already recognized that we are on the cusp of a paradigm shift, listing quantum technologies as critical for Europe's strategic future. The Union must similarly take note of the criticality of the financial conditions experienced by its start-ups and scaleups, and promptly adopt changes to allow its quantum stars to remain global frontrunners. A failure to act decisively will result in a loss of the future quantum champions and push back European quantum competitiveness to the point of no return as has happened with cloud and semiconductor technologies in the past.

2.5.B: Public Funding

2.5.B.1 Building a competitive European QT funding ecosystem

As one of the world's leading forces in quantum research, the European Union is actively driving the second quantum revolution. With a steadfast commitment to advancing quantum technologies, the European Commission has established a comprehensive public funding ecosystem. Europe ranks second in the world, behind China[8]. The total funding announced at all levels of government underscores Europe's strong commitment to advancing quantum research and development.

The 10-year Quantum Flagship programme with a budget of EUR 1 billion is facilitating investment in quantum research and innovation. The Quantum Flagship is to accelerate the development and deployment of quantum technologies across a wide range of applications. It encompasses quantum communication, quantum computing, quantum simulation, quantum sensing and metrology, and basic quantum science. It will drive the translation of scientific knowledge into tangible applications and solutions. During the ramp-up phase (2018-2021) 21 R&D projects were initiated. This phase witnessed remarkable achievements, including the establishment of 25 start-ups, filing of 105 patents, and publication of more than 1300 scientific papers. Continuing and expanding investments in quantum research is of utmost importance for Europe, as it lays the groundwork for future industrial advancements.

The European Union has also demonstrated its commitment to the deployment of quantum technologies by making dedicated investments in key infrastructure areas, such as Quantum Communication through the EuroQCI (European Quantum Communication Infrastructure) and Quantum Computing & Simulation through the EuroQCS (European Quantum Computing & Simulation Infrastructure). The EuroQCI initiative represents a collaborative endeavour between the European Commission, all 27 EU Member States, and the European Space Agency (ESA). It aims to design, develop, and deploy a state-of-the-art quantum communication infrastructure that encompasses both terrestrial and space segments. The terrestrial segment relies on fiber communications networks that interconnect strategic sites at national and cross-border levels. Simultaneously, the space segment leverages satellites, forming an integral part of IRIS², the EU's new space-based secure communication system. By combining terrestrial and space-based capabilities, EuroQCI seeks to establish highly secure and reliable quantum communication networks, enabling breakthroughs in areas such as secure data transmission and quantum cryptography.
In parallel, the EuroQCS initiative focuses on advancing the infrastructure for Quantum Computing & Simulation. This endeavor aims to integrate quantum computers and simulators into a European supercomputing infrastructure to facilitate ground breaking research, simulations, and computations in various fields. The quantum computers are integrated into the existing supercomputers at the selected hosting entities. Currently, six sites across the European Union (EU) have been selected to host and operate the first EuroHPC quantum computers. These include Czech Republic, Germany, Spain, France, Italy, and Poland. The quantum computers will primarily be available for research and development purposes to European users, regardless of their location within Europe. They will benefit scientific communities, industry, and the public sector.

The investments in EuroQCI and EuroQCS underline the EU commitment to creating a robust and comprehensive quantum infrastructure in Europe as they enable researchers, developers, and businesses to leverage the full potential of quantum technologies, ultimately contributing to economic growth, scientific breakthroughs, and the advancement of society as a whole.

For the further industrialisation of quantum technologies, the European Chips Act is set to play a pivotal role in propelling the industrialization of quantum technologies. This comprehensive legislative initiative focuses on advancing various aspects of quantum chip development, including design, prototyping, and manufacturing. Recognizing the significance of quantum chips as the building blocks of quantum computing and other quantum-enabled applications, the European Chips Act aims to foster Europe's capabilities in this critical area.

Europe possesses exceptional research capabilities, a wealth of quantum experts, and visionary startups, making it well-equipped to establish a globally-leading quantum industry within its own borders.

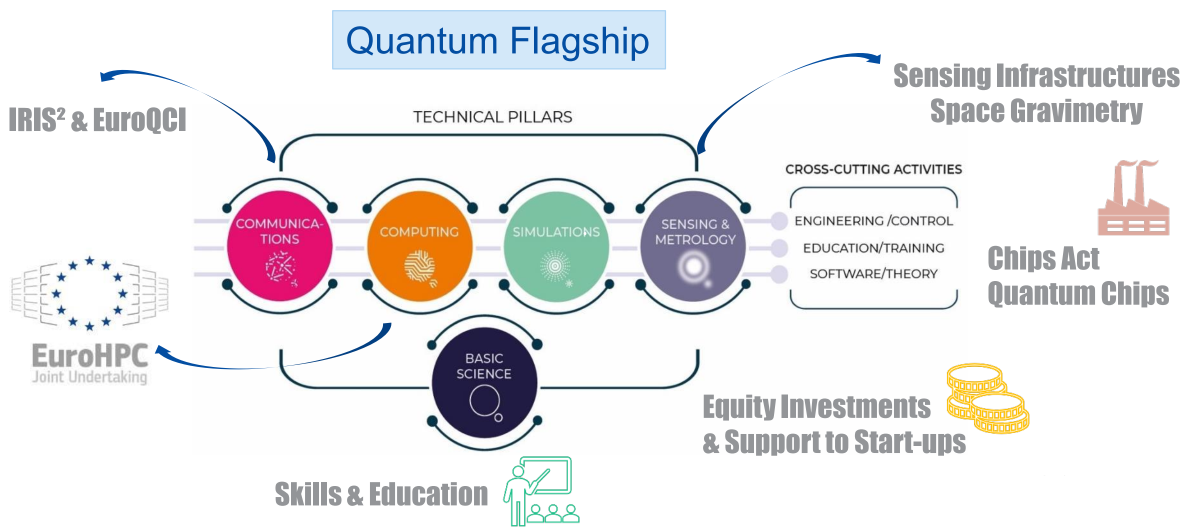

Figure 2.5.2: European Commission initiatives building the European Quantum Ecosystem [Source: European Commission]

2.5.B.2 Member states R&I funding programmes and initiatives

After the three-year long ramp-up phase of the Quantum Flagship successfully ended in 2022, the delivered results have surpassed expectations in all of its five pillars and met all the expected Key Performance Indicators (KPIs). Meanwhile the EC has been expanding its own agenda and investments in Quantum Technology (QT), which now include along with the second-phase of the Quantum Flagship, the EuroQCI, the EuroQCS, a quantum component in the European Chips Act, and a dedicated European Innovation Council (EIC) Pathfinder Challenge. There are also significant efforts in training, innovation, and international relations with major players outside Europe, and

the co-funding of research projects' calls issued by QuantERA, a European network comprising 39 research funding organizations from 31 countries.
Following the EC trend, over the last two years many European Member States (MS) — including Belgium, Bulgaria, Czech Republic, Finland, France, Germany Greece, Hungary, Italy, Latvia, Netherlands, Slovakia — launched their own National Quantum Initiatives (NQIs) dedicated to the development of QT. Overall, this corresponds currently to a total investment in excess of 5.7 billion Euro over a five-year period dedicated to advancing all QT pillars as well as the corresponding enabling sciences and technologies, training, and innovation.

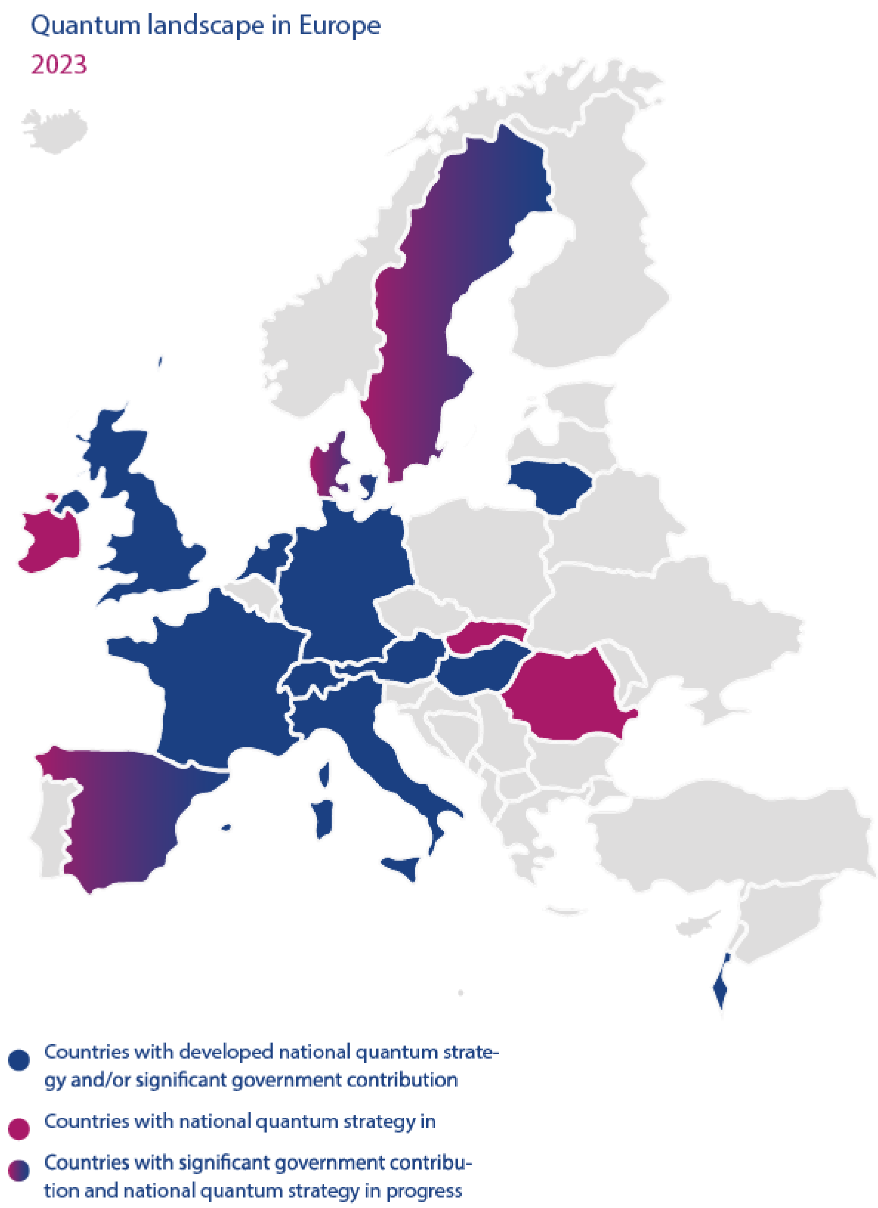

Figure 2.5.3: Quantum landscape in Europe (Source: QuantERA report)

Thus, Europe has established a solid basis for leading the global QT race, securing funding to both develop the most promising QTs and introduce new ones through the advancing of quantum basic science, which has been so far pivotal in sustaining the continuous progress in the field. However, to achieve this leadership role, an unprecedented degree of coordination will be required, with a clear engagement of the EC, the European Quantum Industry Consortium (QuIC) and the NQIs at the MS government levels. This new layer of policy coordination will be needed to ensure that all the EC and MS ongoing and planned initiatives and infrastructures can grow and expand in a coherent, sustainable, and integrated way across the entire Union. This is particularly relevant for the EuroQCS and EuroQCI infrastructures, which have an intrinsic transnational dimension, making it mandatory that the plurality of MS voices can be heard.

The first step in this direction has been taken by the Quantum Community Network (one of the three Governing Bodies of the Quantum Flagship) with the proposal for the creation of a European Network of National Quantum Initiatives contributing to the coherent development of all QT efforts in Europe, with the goals to:

- Increase the national and international impact and visibility of all actions involving Quantum Technologies within Europe.
- Promote bilateral and multilateral cooperation between different NQIs at the level of research & development, innovation, education, and training, exploiting the synergies between academia and industry.
- Establish a common interface between NQIs and the European Commission, and promote the alignment of the different strategies and a regulatory framework in Quantum Technologies.
- Exchange good practices in the development of national agendas, and contribute to the emergence of national quantum initiatives in all EU countries.
- Establish a coordinated basis for cooperation with major players outside Europe and for promoting the creation of international standards in Quantum Technologies.
- Develop joint engagement with the public, including to promote Quantum Technologies as a career perspective and contribute to fill the skills gap across Europe.

Below, we highlight the list of the current National Quantum Initiatives of each Member State up to date:

1. Dedicated national QT programmes and initiatives, 2023

Country	National strategy/agenda/ programme	Other national initiatives	Budget	Duration	New development*
Austria		Quantum Austria Funding Initiative	€107 M – shared between FFG and FWF and contains administrative expenses	2021-2026	Yes
Denmark	Danish Strategy for Quantum Technology 2024-2027 (DSQT)	Governmental budget allocation for QT; Mapping of the QT area	DSQT: approx.. €150 M Governmental budget allocation for QT call in 2023: €20 M	DSQT: 2024-2027 Governmental budget allocation for QT: 2023	Yes
Estonia		Estonian Research, Development, Innovation and Entrepreneurship Strategy for 2021-2035			Yes
Finland		Finnish Quantum Agenda			
France	Quantum Plan – France National Quantum Strategy		€1.8 billion	2021-2025	Yes
Germany	Economic Stimulus Package (ESP)	Quantum Systems (QS)	ESP: €2 billion	ESP 2020-2025 QS 2022-2032	Yes
Greece		Operational Programme for Competitiveness, Entrepreneurship, and Innovation 2021-2028 (EPAnEK) and National Research and Innovation Strategy for Smart Specialisation 2021-2027 (RIS) (Greece)			

Country	National strategy/agenda/ programme	Other national initiatives	Budget	Duration	New development*
Hungary	Quantum Information National Laboratory		€15 M	2020-2026	Yes
Ireland	In progress				Yes
Israel	Israel National Quantum Initiative (INQI)		~€350 M	2020-2025	Yes
Italy	Italian Plan for Recovery and Resilience (PNRR); M4 Education and Research – Component 2 From research to business		PNRR: €170 M	2020-2025	Yes
Latvia	European Union Recovery and Resilience Mechanism component “Digital Transformation” (DT)		€6.19 M + forecast of approx. € 1 M investment from other sources	2022-2026	Yes
Luxembourg		Luxembourg National Research Priorities			
Netherlands	Quantum Delta NL programme		QDNL: €615 M	2021-2028	Yes
Norway		Long-term Plan for Research and Higher Education 2023-2032 (Norway) – highlights quantum technologies as a particularly prioritised area for research and research-driven innovation			

Country	National strategy/agenda/ programme	Other national initiatives	Budget	Duration	New development*
Romania	In progress	National 4th Plan of the new Strategy for research, innovation and smart specialisation (2022-2027; Romania), included Digital economy and space technologies & Advanced functional materials			Yes
Slovakia	In progress				Yes
Spain	In progress	Quantum Spain (QS) Complementary Plan for Quantum Communications (PQC)	QS: €22 M PQC: €73 M		Yes
Sweden	In progress	Wallenberg Centre for Quantum Technology (WACQT)	€88,5 M	2018-2029	Yes
Switzerland	Swiss Quantum Initiative (SQI)	SPIN – Spin Qubits in Silicon	SQI: CHF 10 M SPIN: CHF 40 M	SQI: 2023-2024 additional federal funding is planned for 2025-2028. SPIN: 2020-2023	Yes
Türkiye		11th Development Plan (2019-2023) of Türkiye			
United Kingdom	National Quantum Strategy (NQS) National Quantum Technologies Programme (NQTP)		NQS: £ 2.5 billion NQTP: £ 1 billion	NQS: 2023-2033 NQTP: 2014-2024	Yes

**in comparison with previous publication Quantum Technologies – Public Policies in Europe, 2020*

2.5.B.3 Towards a fully integrated European funding ecosystem

Within the technologies provided by the Quantum Flagship during its first years, the results from basic research are developed into concrete technology deliverables in all areas as described in the previous version of the SRIA, which also tracks dependencies from international suppliers of critical components. The Chips for Europe initiative will create the necessary capabilities to overcome those dependencies and to industrialize the Flagship's technology prototypes. The resulting products are going to be potentially commercialized by Europe's own quantum entrepreneurship, with the support by public investment funds to grow a full quantum ecosystem. European infrastructures (both terrestrial and in space) will contribute to bootstrap the quantum market by adopting those products and integrating them into the fabric of the future quantum web.

Recommendations

- To realize this vision, the EU needs a tightly integrated ecosystem of successful investments in innovation, infrastructure, entrepreneurship and skills in quantum technologies. The scope goes even beyond the current MFF, both in terms of timescale and synergy with the growing number of national quantum initiatives, as well as in terms of cooperation with like-minded countries beyond Europe's borders.
- In order to develop this leadership in quantum technologies, the EU will need to strengthen the link between research and industrial development targets with concrete deliverables in all areas, integrating and monitoring all the industrial and R&D ongoing initiatives to deliver a quantum advantage for societal through quantum computers and simulators, implement a pan-European entanglement-based quantum network, including quantum repeaters for device-independent secure quantum communication; deploy a pan-European network of quantum gravimeters for high-resolution Earth observation and predictive natural resources management; as well as deploying optical quantum clocks in Galileo for high-precision navigation while consolidating and maintaining the EU basic research effort.
- Additionally, the EU will need to foster industrialization of quantum devices, deepen the integration of the European quantum industry ecosystem by leveraging the existing European Quantum Industry Consortium and with specific measures like de-risking via attractive co-financing of proof-of-concept R&D undertakings between SMEs and large end-users.
- In order to facilitate the creation of a fully integrated European funding ecosystem it is key to for the European Commission to coordinate with the national quantum initiatives and funding organizations for future sustainability of upcoming quantum infrastructures by establishing a structure bringing together all MS with the Commission for coordinating their funding programmes, for discussing international cooperation matters, and for facilitating the creation of future partnerships.

2.6

Intellectual Property Rights (Assets)

Intellectual property rights, in particular patents, are an important business tool for companies and organizations in quantum. It not only provides an exclusive right to exclude others to perform certain activities with respect to products and processes (using, selling, importing, marketing, etc.), but also can serve multiple other purposes such as:

- Creating prior art to block others from patenting
- Create a basis for licensing out technology
- Create an intangible asset that can be used as a collateral
- Control IP rights during a cooperation
- Create leverage in negotiations
- Serve as a marketing or advertising tool
- Give access to special fiscal status under national legislation
- Attract investors
- Create freedom to operate
- Safeguard ownership of the technology when people leave the company

It is of utmost importance that SMEs, in particular startups and spinoff understand how IP can be used in their organization to gain and maintain competitive advantage.

Another mechanism to protect technology is the use of trade secrets, which relies on keeping certain knowledge about a piece of technology secret. A trade secrets is not an exclusive right, it is based on contractual relation such as a non-disclosure agreement and confidentiality clauses in labor contracts and commercial agreements (e.g. cooperation agreements, R&D agreements, etc.).

Reliance on trade secrets as the only means to protect an invention is not a good idea. This is because of the nature of a trade secret:

• Once it is lost, i.e., becomes public, it is lost forever.
• Trade secret does not protect you from third party patents[1].
• Trade secrets are difficult to maintain in an environment with multiple employee changes or multi-party cooperations.

The WG IPT will identify best IP practices for inventions in quantum illustrating that patents and trade secrets are not mutually exclusive and that in technical fields such as quantum, photonics and semiconductors effective protection can be obtained by a combination of patents and trade secrets.

2.6.A: Patentable inventions in quantum

Inventions in quantum relate to hardware, but also to a large extend on “software” (e.g., algorithms in the form of quantum circuits describing operations to be executed on a quantum computer) and protocols (e.g., QKD protocols). These patent applications on software and algorithms in quantum typically cover use cases (applications), algorithmic improvements, protocols and control functions.

The so-called CPC classification scheme for patent applications that is used by the European Patent office shows that topics like quantum algorithms, quantum circuits, error correction schemes, simulations, quantum machine learning and cloud-based quantum computing are subject of patent applications.

Software and algorithms can be patented in Europe. The legal framework and rules are laid down in the Guidelines for examination (the Guidelines) of the European Patent Office (EPO). According to the Guidelines, computer implemented inventions – software inventions, including inventions based on algorithms and AI – are patentable in Europe if an invention has technical character.

Software as a high-level abstraction from the underlying hardware has technical character only if one of the two following situations apply:

- The software or algorithm deals with a specific application[2] identified by the case law of the EPO Boards of Appeal as being “technical”
- The software is adapted to the internal functioning[3] of the computer.

These rules provide a relatively clear framework of what is patentable and what is not patentable. Hence, software or an algorithm that runs on a conventional computer can only be patented if it deals with a specific technical application. This situation is problematic in the sense that algorithmic innovations that have multiple applications (e.g., a clever convolutional neural network architecture) and are not adapted to the internal functioning of the computer cannot be patented in a generic way, only in specific ways, namely insofar they are limited to “technical applications” as decided by the EPO.

Currently the Guidelines does not provide explicit rules regarding software related inventions in quantum. The recent decision G1/19 of the Enlarged Board of Appeal of the EPO regarding the patentability of simulations mentions that quantum computing may provide computer power to perform certain simulations that is not available from a standard computer.

For the EPO inventions on software and algorithms in quantum, including quantum machine learning, are new and the Guidelines do not provide clear rules how to deal with these inventions. A recent presentation of the EPO about examination of inventions in quantum suggests that the rules related to “conventional” (non-quantum) computer implemented inventions should be applied to quantum in an analogous way.

The WG IPT has contact with the EPO and intends to set up an ongoing discussion with the EPO on substantive examination of patent applications in quantum by the EPO with the aim to produce some clear rules on the possibilities regarding patenting software and algorithms in quantum, which would allow effective protection of inventions, including software and algorithms, in quantum.

2.6.B: The patent landscape in quantum

The WG IPT has conducted a patent landscape analysis regarding patent filings on quantum technology.

The last ten years have seen a significant increase in the development of new IP in quantum research, resulting in a considerable number of patent applications and registrations. This reflects the increased interest in translating new research on quantum technologies into new quantum products.

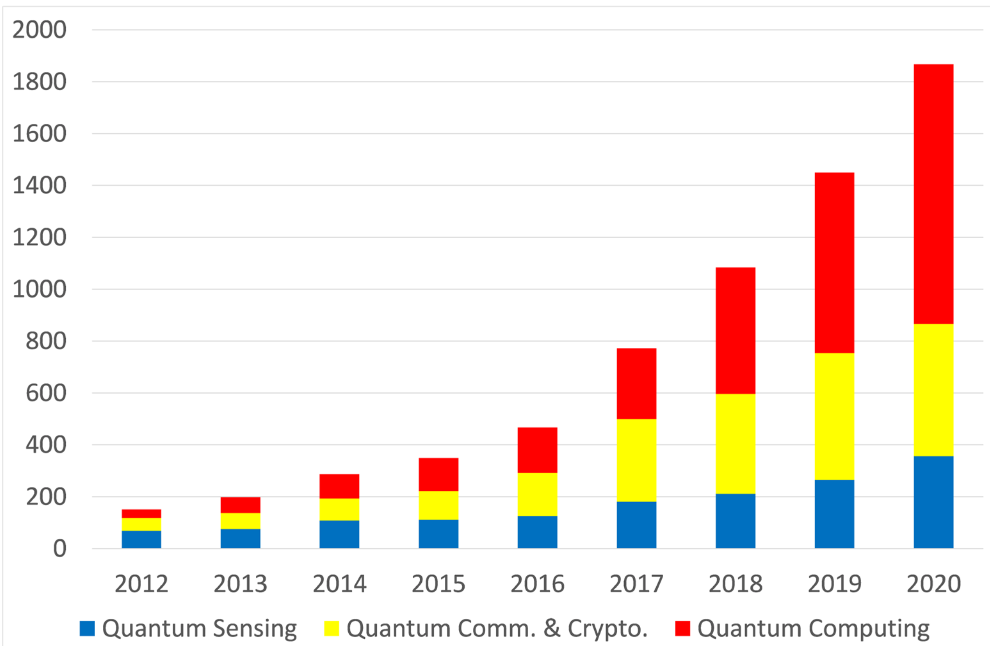

Figure 2.6.1: Patents filed in quantum sectors

The current patent landscape is dominated by quantum computing followed by quantum communications and crypto. As of now, these patent families reflect low TRL activities and are experiencing increased interest and funding from national initiatives or large groups as well as start-ups, indicating the accelerating investment related to Quantum Technologies.

Regarding European position in terms of patenting, we must recognize that Europe is lagging far behind USA and China, with less than 10% of worldwide patent families. The global leaders are of course USA and China in terms of Quantum Technologies patents.

If we look at the situation in the EPO states by country or region of origin, Europe is also lagging behind USA, with less than 30% of "EP" European Patents originating from a European country.

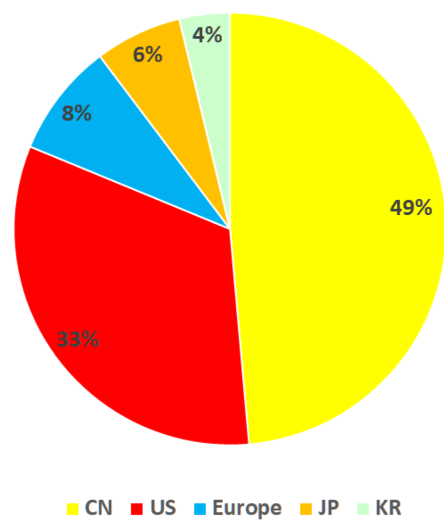

Figure 2.6.2: Percentage of the total number of patent families.

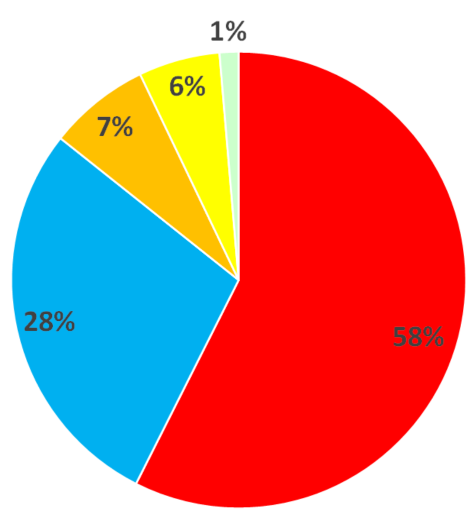

Figure 2.6.3: Percentage of the total number of patent families for European Patents

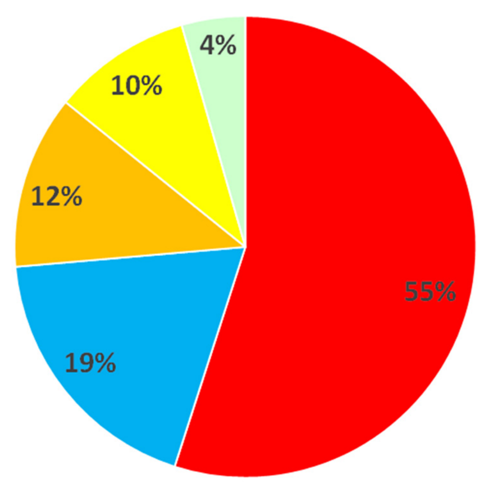

Figure 2.6.4: Percentage of the total number of patented inventions in two countries or more by country of origin

It is well known that very few Chinese first filings are extended outside China. However, even considering patents families with patents pending in two (or more) countries, Europe is not in a good position.

Facing such a difference in terms of numbers of patents puts of course Europe, and European companies, at risk of being preventing to use such technologies.

It is consequently a real matter of autonomy and “sovereignty” for Europe and European companies to increase significantly the number of patent families in the Quantum world.

The WG IPT will continue monitoring the patent landscape. The WG has also contact with the EPO about patent filing information in quantum technology and use this information to inform and educate the QuIC members and other relevant bodies (EPO and EU). For example, the QuIC WG will help the EPO in reviewing drafts of so-called Patent Insights Reports on quantum (in particular Patent Insights Reports on quantum metrology and sensing, quantum computing, quantum simulations and quantum communications).

Objectives and Recommendations

- Establishing a more balanced situation in terms of patents
  - Liaise with European patent Office, so as to:
  Build together a shared view of the current European landscape,
  Identify the brakes to patenting in Europe
  Promote EPO work and efforts regarding different types of trainings in Quantum Technologies: for startups, R&D teams, academics, as well as patent attorneys
- Improve general knowledge regarding patenting in QT, especially towards SMEs or startups
- Establishing clear rules on the patentability and establish an IP community with strong competence in quantum, with the EPO and the European IPR helpdesk
- Standard Essential Patents play an important role in standardization, especially for Communication and Cryptography, where interoperability between equipment is key. As such, WG IPT shall liaise with European Union and with Standard Development Organizations (such as ETSI, IEEE, ISO, etc.) to monitor and study the interplay of patents and standards for quantum technologies and to formulate recommendations towards the QuIC members and/or relevant bodies

[1] Directive (EU) 2016/943 on harmonization of protection of trade secrets and the implementation of this directive in national law provides improved protection against unlawful acquisition, use and/or disclosure of trade secrets. It does not however provide an exclusive right, i.e. a right to exclude others.
[2] Based on this rule, software in the medical field, image processing and encryption is technical and thus patentable, while software on natural language processing, logistics and finance is in principle not technical and thus not patentable.
[3] Based on this rule, software that is adapted to a specific computer architecture, e.g., the use of a GPU as a co-processor in AI applications or software that is adapted to run on a computer that has a parallel processing architecture is technical.

2.7

International Collaboration & Export Control Regulation

2.7.A: Introduction

Geopolitics is an increasing force acting on the evolution of the global quantum market. Although some quantum technologies are more mature towards being established technologies, such as gravity sensors, many remain in their infancy, other are more trendy. The early and broad application of export-control regulation on the fear of future potential rather than current performances runs the risk of halting the growth of certain quantum-technology sectors altogether. It is thus important for the European Commission to engage in early discussions with like-minded international partners, notably the United States via the newly created Trade and Technology Council (TTC), on common approaches in connection with the quantum industry. Nurturing positive relations with like-minded non-EU partners will be essential for the growth of the EU quantum industry.

International collaboration is interconnected with other topics such as education, talent movement, and standardisation.

2.7.B: High-level goals

Quantum technology is expected to have significant economic implications in the future. International collaborations enable the creation of larger, more competitive ecosystems, attracting investment and fostering innovation. Collaborative projects can lead to the development of new technologies, products, and services, driving economic growth and job creation. By combining efforts, researchers can tackle bigger challenges and contribute to advancements that benefit society, by sharing their expertise, knowledge and ideas. In addition, collaborations in quantum technology strengthen international partnerships and foster diplomatic relations between countries. Shared scientific goals and successful collaborations can facilitate broader cooperation in various domains, including trade, education, and cultural exchange. These partnerships contribute to building trust and promoting peaceful relations among nations.

On the other hand, the development of international collaborations is highly related to national politics as well as geopolitics issues. Geopolitical factors, such as trade disputes, sanctions, or political differences, can limit international collaborations. These tensions may lead to restrictions on the exchange of knowledge, technology, or funding, making it difficult to establish and sustain cooperative efforts. Therefore, it is essential to have a clear understanding of geopolitical trends.

Before moving to objectives for 2023-2026 and 2027-2030 and to recommendations, it is important to highlight opportunities and risks of international collaborations for the EU. In addition, a framework of collaboration should be clearly identified, to have efficient bilateral discussions and actions.

2.7.C: Opportunities of collaboration for EU

1.Mitigation of resources
Quantum research often requires substantial investments in infrastructure, technology, and human resources. Collaborating across borders allows partners to share the costs and resources associated with research and development. This can help mitigate the financial and logistical constraints that individual countries or institutions may face, enabling more ambitious and impactful projects.

2.Tackling complex challenges
Quantum technologies pose complex challenges that require a multidisciplinary expertise. International collaborations facilitate the convergence of researchers from different fields, such as physics, computer science, materials science, and engineering. This interdisciplinary approach is essential for addressing the complex scientific and technical aspects of quantum technology development and deployment.

3.Policy and standards development
International collaborations facilitate the sharing of best practices and policy frameworks for a responsible development and deployment of quantum technologies. Partnerships between countries or regions can contribute to the establishment of global standards, protocols, and regulations, ensuring ethical use, privacy protection, and security considerations in quantum technology applications.

4.Education and talent
Collaborations provide opportunities for the exchange of students, researchers, and experts between institutions and countries. This enables the transfer of knowledge and skills, enhances training opportunities, and cultivates the next generation of quantum scientists and engineers. International collaborations enrich educational programs, promote cultural diversity, and inspire collaboration across borders.

2.7.D: Risks of international collaborations for EU

1. Funding misalignments and infrastructure disparities
Availability and distribution of funding can differ between regions. Divergent funding priorities, grant systems, and budgetary constraints can make it challenging to synchronize financial support for collaborative projects. Balancing contributions and ensuring equitable sharing of costs can be a potential hurdle.

Disparities in research infrastructure and technological capabilities can hinder collaborations. Uneven access to cutting-edge facilities, quantum computing resources, or specialized equipment may limit the scope of collaborative projects or create an imbalance in contributions from each partner.

2. National security considerations
Some quantum use cases may be related to national security and sovereignty issues. In practice, it is often translated through export restrictions, and regulations on inbound and outbound investments. Compliance with these regulations can be burdensome and may pose challenges when seeking funding or sharing resources across borders.

3. Data privacy and security
Collaborations in quantum technology often involve sharing sensitive data and information. Differences in data protection regulations, privacy laws, and cybersecurity standards between the EU and the US can raise concerns about data privacy, security breaches, and compliance with regulatory frameworks.

4. An evolving regulatory landscape
The regulatory landscape surrounding quantum technologies is still evolving. Policies, regulations, and ethical considerations related to quantum technology can change over time, potentially influencing ongoing collaborations. Staying updated with regulatory developments and adapting collaboration strategies accordingly is important.

2.7.E: Steps of cooperation

The EU has numerous bilateral agreements with foreign countries and not all discussions are at the same state of play. Therefore, before moving on with a specific country, it is important to identify the step of cooperation, to move forward.

Step 1: First approach of collaboration on quantum technologies
Organizing bilateral discussions and workshops to identify common interests and funding opportunities for possible collaborations.

Step 2: Identity topics of collaboration
Identify topics of collaboration, based on EU needs and knowledge of strengths and weaknesses of country A. This identification can take times and discussion between stakeholders, from research and industry, from EU and country A.

Step 3: Establish a framework of cooperation, if it is not done yet
Depending on the state of play of the cooperation with a country A, a framework has to be validated, more or less engaging.

Step 4: Develop a specific collaboration on quantum, involving research and industry
Once a general framework of collaboration is validated, it is important to have a specific axis of cooperation on quantum. Such collaboration should be very practical and involve academic and industry since both are complementary.

Step 5: Develop regular bilateral discussion to support collaborations
To maintain good relations with country A, bilateral discussions should be organized on a regular basis, through international conference or political opportunities.

2.7.F: Objectives for 2023-2030

Those objectives are ambitious and aim to support the development of international collaborations on quantum. It is important to move gradually; therefore, objectives are divided in two sections: short term from 2023 to 2026 and mid-term from 2027 to 2030 and more. Some objectives are in both sections since they are more generic.

→ Objectives by 2023 - 2026

- Develop and implement long-term roadmap for international collaboration strategy, both for academic and industry collaboration (in principle (partly) InCoQFlag final result).
- Reflexion on a roadmap took kit.
- Collaborate with non-EU countries to leverage strengths and counter weaknesses of the EU ecosystem in general.
- Follow/Use e.g. international organizations for international collaboration on dual-use applications of quantum technology (mostly related to quantum sensing).
- Strengthen the position of quantum technology in the Trade and Technology Council and consolidate a clear EU position beforehand.
- Reflexion on IP in international collaboration, common understanding at EU level
- Strengthen collaboration within EU and the understand of European member states strengths and weaknesses.

→ Objectives by 2027-2030

- Update the roadmap took kit.
- Collaborate with non-EU countries to leverage strengths and counter weaknesses of the EU ecosystem in general, based on a priority list.
- Strive towards establishing an EU strategically autonomous/resilient supply chain with reciprocal dependencies: protect and leverage key component manufacturers in EU, while mitigating critical non-EU dependencies.
- Have a forward-looking approach on collaboration with non-EU countries regarding long-term European programmes. Access to infrastructure to non-EU member states. For example:
  International access to EU pilot line or testing infrastructure (Qu-Pilot, Qu-Test).
  Collaboration strategies for integrated quantum-HPC infrastructure (EuroHPC).
  Long term: connecting quantum computers e.g. across the Atlantic.
  Satellite connections to non-EU QKD networks (EuroQCI).
- Develop a strategy regarding the usage of EU vs. non-EU large-scale fault-tolerant quantum computing systems (especially to counter the potential dominance of US companies, although we do not have to be explicit about this).
- Follow/Use e.g. international organizations for international collaboration on dual-use applications of quantum technology (mostly related to quantum sensing).
- Strengthen the position of quantum technology in the Trade and Technology Council.
- Quantum technology advancements often involve valuable intellectual property. Concerns about intellectual property protection and ownership can arise, particularly when collaborating across borders. Differing regulations and legal frameworks may pose challenges in managing and safeguarding intellectual property rights.

Recommendations:

- The European Commission and the European quantum industry to engage in early discussions with like-minded international counterparts on quantum technologies.
- Collaborate with non-EU countries to leverage strengths and counter weaknesses of the EU ecosystem in general.
- Connect ecosystems of EU member states to enforce position of the EU as a whole.
- Align EU and member states position on international cooperation The Technology and Trade Council (TTC) may be an appropriate vehicle for such actions.
- Follow/Use e.g. international organizations for international collaboration on dual-use applications of quantum technology.
- Accelerated progress and knowledge exchange: Collaboration enables researchers to pool their expertise, share knowledge, and exchange ideas. This accelerates the pace of scientific discovery and technological advancements in quantum technology. By leveraging diverse perspectives and complementary skills, international collaborations can lead to breakthroughs that might not be achieved through isolated efforts.
- Quantum technology has significant implications for national security. Governments may prioritize protecting sensitive information and technologies, leading to restrictions on international collaboration in specific areas of quantum research. Balancing scientific openness with national security concerns can be a complex issue. Limit, export restriction.
- International cooperation should be on research and industry, including both stakeholders.
- International collaborations provide access to a broader pool of talent, combining the expertise of researchers from different regions and institutions. This diversity in skills, experiences, and backgrounds can foster innovative approaches and interdisciplinary collaborations. Additionally, shared resources such as research facilities, computational resources, and experimental equipment can be leveraged to enhance research capabilities.

2.7.G: Export control

The quantum domain involves many stakeholders from established companies to start-ups, from universities to research organisations from different regions in the world. No region holds, at present, dominance over this technology. Different interpretations of national security and economic security lead to diverging efforts to safeguard critical technological advances and to limit the innovation potential of other key players (being a competitor, systemic rival, or adversary).

Quantum technologies are high on the agenda of foreign-policy instruments such as export controls, but also new policy instruments related to outbound investments and avoiding unwanted technological leakage. Such tools are not to be seen as mere restrictions to international collaborations, but important pillars of safeguarding the security interests of countries.

Quantum technologies are at the heart of gaining a geo-strategic and geo-economic lead by China, the U.S. and the EU. Via national plans they develop promote opportunities and control hurdles for attracting talent, investments, and production capabilities. There are concerns that the EU is being squeezed in the middle of the competition between China and U.S., and that the EU's efforts to bolster competitiveness and resilience will not suffice.

To maintain and grow the technological edge of the EU in quantum technologies, the impact of regulatory instruments needs to be carefully assessed against supporting research and the enabling of scientists to exchange their knowledge in a secure environment while preventing misuse. This requires concerted dialogue efforts at both EU Member States, EU and international (such as EU-US Trade and Technology Council) levels from industry to universities and research organisations ('academia') active in quantum technologies.

In the area of export controls some outreach activities have already taken place: DG Trade developed already an Export Control Factsheet on Quantum Technologies[1] and DG Trade together with EU Member States established a Technical Expert Group on Emerging Technologies, including quantum technologies.

Foreign-policy instruments in the EU have a mixture of EU-level and EU-Member State level competences as we have seen in Spain that issued in May 2023 national controls on certain quantum technologies ahead of decision in the Wassenaar Arrangement or other controls in other EU Member States. This allows for fine-tuning national controls and outreach to stakeholders based on the own technological capabilities and policy considerations. But this also limits the level-playing field across the EU for industry and academia. Engagement of academia and industry in developing new controls for quantum technologies of concern is crucial to provide the necessary predictability and certainty to allow stakeholders to plan and execute projects in the field of quantum technologies.

[1] Included in the DG TRADE document:" Emerging Technologies - Developments in the Context of Dual-Use Export Controls" https://circabc.europa.eu/ui/group/654251c7-f897-4098-afc3-6eb39477797e/library/08c609c4-45bf-4e33-bfa7-960ba955ef55/details

Objectives and Recommendations

- A level-playing field needs to be ascertained via a dialogue with all relevant academia and industry stakeholders including policy makers at the European Commission, export control authorities of the EU Member States and the EU-US Trade and Technology Council.

2.8

Social and ethical values

Social values are integral in guiding the development and use of quantum technologies. These values include accountability, transparency, and inclusivity. Researchers and practitioners in quantum technologies should be accountable to society, ensuring that their work is conducted in a responsible and transparent manner, and that the benefits and risks are shared equitably among all stakeholders. Inclusivity is also essential, as diverse perspectives and backgrounds must be considered to ensure that quantum technologies are developed and used in a way that promotes fairness and avoids exacerbating existing societal inequalities.

Ethical values play a pivotal role in shaping the ethical implications of quantum technologies. Ethical considerations such as privacy, security, and the responsible use of quantum technologies are paramount. Quantum technologies have the potential to significantly impact data security and privacy, and it is essential to ensure that the development and use of quantum technologies adhere to ethical principles that protect the rights and well-being of individuals and society as a whole.

The responsible development and use of quantum technologies also involve considerations of the potential societal and environmental impacts. For instance, the potential computational power of quantum computers could have far-reaching consequences for various industries, including finance, cryptography, and drug discovery. Therefore, it is essential to approach the advancement of quantum technologies with a deep sense of ethical responsibility, considering the potential implications for society, the environment, and future generations.

Therefore, social and ethical values are critical in shaping the development and use of quantum technologies. Responsible practices that prioritize accountability, transparency, inclusivity, privacy, security, and societal well-being are vital to ensure that quantum technologies are developed and used in a way that benefits humanity as a whole while mitigating potential risks and ethical dilemmas. It is imperative for stakeholders in the field of quantum technologies to engage in ongoing dialogue and thoughtful consideration of social and ethical values alongside technological advancements to ensure that these technologies are harnessed for the greater good.

2.8.A: Equality, Diversity and Inclusion

Equality, diversity and inclusion issues are wide-ranging and include gender equality and inclusiveness policies dealing with gender balance, pregnancy and parental leave, parenting and other care responsibilities, as well as policies to achieve equal rights for the LGBTIQ+ community. Inclusiveness is the objective of these policies, bringing diversity not only in gender but in combination with other minorities or discriminated communities, related to race/ ethnicity, socio-economic background, age, living location, religion, indigenous status, cultural and linguistic disabilities, among others (EC, 2020).

Diversity in research, science, and technology is important in driving innovation, fostering creativity, and addressing complex global challenges. From academia to industry, diverse representation in research, science, and technology enriches decision-making processes, enhances problem-solving capabilities, and promotes inclusivity. Embracing diversity in all its forms, including but not limited to race, gender, ethnicity, sexual orientation, socio-economic status, and disability, is not just a matter of social justice, but also a strategic imperative for advancing knowledge, creating meaningful solutions, and promoting sustainable development.

Overcoming barriers to gender equality, diversity and inclusion within the quantum technologies ecosystem is crucial, as it presents challenges in areas such as recruitment, talent retention, education, and promotion of individuals. Thus, the quantum community is committed to the ERA framework for gender equality and inclusiveness and contributes to its goals.

Gender can be used as a Key Performance Indicator (KPI) to measure and track diversity, so that needed improvements in this diversity dimension reflect improvements in diversity overall. It is thus that specific policies and actions directed to improve gender equality are needed. Gender refers to the different roles, behaviours, characteristics, and identities that society ascribes to « feminine « and « masculine » behaviours (EC, 2020). However, gender is multidimensional and needs to be viewed from an intersectional perspective. Using gender as a KPI of diversity involves collecting and analysing gender statistics to assess the effectiveness of gender and diversity initiatives, policies, and practices, and to guide decision-making and action plans.

Fairness and proven positive impact on productivity and innovation are basic incentives for action. In quantum technologies the gender imbalance is about 20/80, which notably points out a deficit in a disruptive and innovative community. This also results in a non-inclusive environment and thus suboptimal attractivity and retention. Actions and structures at all levels must change this detrimental situation to create an ecosystem that promotes and enacts gender equality. Notably, the number and visibility of women scientists have to significantly increase at each level of the value chain of quantum technologies, from basic science to the related industries, and to the future workforce of the field. Funding is needed to shift mind-sets and disrupt inequality. Blind spots will in particular be removed by enforcing a gender issues section in all research and innovation calls.

Gender equality remains one of the largest challenges in the diversity of the QT ecosystem. This is a problem that implicates all stakeholders, many of which are beyond the QT community, like school educators and students, parents, families and general public, and of course the society we line in as a whole. However, the QT community has to take its share and be aware of the need to be an example of progress towards gender equality and inclusiveness, accompanying the necessary changes and having an impact on society in this objective. Furthermore, resources allocated to address these issues are limited and clearly insufficient.

There are two main things that must happen to address the current gender, or for that matter, under-represented communities' imbalance:

1. Have more girls and women- especially those coming from under-represented communities – as well as LGBTIQ+ people in STEM careers that lead them to pursuing quantum careers, increasing the number of potential women and a diverse future workforce, and
2. Make our ecosystem more inclusive and sensitive towards work-life balance, and work towards a diverse representation at all career levels.

The first point needs more long-term actions and local operations through the school systems and other education levels, as well as engagement activities with the general public. It is crucial to increase the number of diverse profiles moving towards QTs.

The quantum community can help with the first point by encouraging quantum funded projects to conduct RRI activities focused on gender equality and inclusiveness, and with the second point by making our community more inclusive, which will attract and engage a more diverse workforce.

Keeping this in mind, and with the aim of making our ecosystem more inclusive, these are immediate action points to take:

Statistics and KPI methodologies in place: A procedure to collect and monitor EDI-related information including quantitative data and qualitative aspects that will allow us to understand the actual situation in terms of EDI and existing ecosystem as well as measure the impact of the measures that the Quantum Flagship is taking. This will also raise awareness of imbalance.

Recommendations

- Regular surveys using the same methodology should be launched to monitor the status of EDI within the quantum community
- Have the Quantum Flagship projects publicly report statistical information around diversity.

Charter for EDI at conferences created: The Quantum Flagship will create a charter for gender equality at conferences that event and conference organisers will have to follow for the Quantum Flagship to endorse them by helping with their dissemination and even participating in them.

Recommendations

- A code of conduct that establishes minimum requirements to organise/ support/ participate in an event. For instance, no acceptance to participate in a panel if there are no (not enough) women in the panel, assessing neutral, respectful communications, and ensuring good practices are actively questioned, researched and enforced by an efficient organizational chart (chairperson duty, assigned task for committee members), non-harassment policy and identified set of contact persons to deal with issues and guide, etc.
- Requirement to record the gender breakdown of speakers (invited and not) participants, organizing committees and panel members and to upload this breakdown on a Flagship dedicated website for each event/conference. Obligation to read the code of conduct at the start of the event, and include announcement of the gender diversity of the event (in terms of speakers and participants).

Increase the participation of under-represented groups in events, commissions and fora: While the results are further upstream and longer term, it is important to have mechanisms at the European level that promote gender equality and inclusiveness in quantum events and decision-making bodies. An important element for that to happen is to compensate for the financial burden that such participation means for these communities, as they often suffer of inequality either through the salaries (because of their gender or geographical location), because they have added burdens as they need to take care of a family member (e.g. underage children, sick or dependent person) and need to put in place solutions while they are away participating in conferences, commissions,… This can be channelled through overarching funding schemes that go beyond quantum-related funding or through dedicated budget within the quantum programmes.

Recommendations

- Allow a budget so that members of the European quantum community can apply for funding of specific support that is needed to participate in quantum-related congresses, meetings, and other specific events. E.g. travel costs for caretaker, or hiring of caretakers that stay home, rental of equipment such as strollers, wheelchair, etc. It should be an easy-to apply application.
- Create and make it publicly available a list of PIs in Quantum Technology Ecosystem targeting 50% women where the people with decision-making capacity can be found for the need of event organisers and consultancy.

Bring cohesion and empower the under-represented communities in quantum: Create mechanisms that encourage a quantum network around EDI that helps raising awareness of EDI activities, sharing of best practices, input to policy makers, strengthen more diverse scientific collaborations and create the right spaces to promote mentorships and gathering of experiences and ideas, key in the retaining of talent and changing the environment.

Recommendations

- Creation of a Quantum EDI network.
- Organisation of and participation in events and networking opportunities that support the creation of mentoring relationships.
- Organisation of a diversity in quantum event or partnering with existing events that give visibility to the under-represented communities, promotes inclusive and diverse scientific collaborations, and provides a forum to meet, network, and discuss EDI issues.

Unconscious bias training program for the quantum community: biases affect everyone, regardless of their own personal beliefs and opinions; signs of these behaviours in science are everywhere, starting in schools and continuing through all levels of the career ladder. This translates among other things, into women in science earning less, being less likely to be promoted or receive letters of recommendation, and more likely to quit altogether. Training is an essential part of the professional development of scientists and engineers in academia and industry, and to correct the unconscious bias, specialised training is needed and very frequent reminder (e.g. before each panel) and/or a key person being in charge to check (just as the formal role of chairperson) is needed.

Recommendations

- All quantum projects under the EU umbrella should undergo training on gender equality and inclusiveness, which should be included in the grant agreement, as a mandatory action at the start of the project and for all members of the projects, no matter their seniority or gender. Budget for this should be included in their proposals, and training should be carried out by professional trainers.

Creation of outreach programs (with additional funding for it): it is key to increase the number of potential professionals in quantum technologies, and for that, we need to increase the number of diverse students in STEM careers, especially those that show a more direct link to quantum technologies (e.g. Physics, Engineering, Mathematics and Computer science). For that, we need outreach programs directed to female and other under-represented high school students and STEM undergraduates, to promote and increase visibility of professional opportunities that quantum technologies provide to them.

Recommendations

- Creation of a quantum outreach office that creates a platform with outreach content in different languages based on existing materials or the creation of new ones.
- Align with EC Flagship targets and actions.
- A number of women in boards - particularly in the SAB and FCO - at least matching the percentage of women in the QT community, with the objective for this value to achieve the target of 50%.
- A target of 40% women-led companies invited to pitch their projects.

2.8.B: Widening the quantum community

As multiple studies and matrices show there is a persistent disbalance in economical performance between the countries in the “core” of the EU and those in its Eastern and Southern wings. This fact is promoted also into a disbalance in R&I intensity, in R&I outcomes, and in subsequent deployment of scientific results and other findings.

This analysis applies unfortunately also to quantum R&I where some of the best minds come or reside in the widening countries (CEEC) yet major European project hardly benefit therefrom as these experts and their institutions are not partners these projects.

To reap the benefits of quantum R&I in the widening countries and to give their researchers opportunity to participate on equal footing on our research, development demonstration and deployment activities, the issue shall be tackled as follows :

Recommendations

- In future projects, whenever feasible, special effort shall be to promote the projects early in their conception phase to relevant specific widening institutions and/or individuals. If requested, special briefings to the potential widening partners will be offered.
- In order to bring experts from widening countries and from more advanced countries together, an effort will be made to organize, whenever feasible, relevant scientific conferences and workshops in the QT field in the widening countries.
- If of equal capacity and potential contribution to the project, care will be taken to prioritize participation of widening partners.
- All running projects will explore the opportunity to add additional partners from widening countries on board via so-called Hop-on facility. This additional participation may but doesn’t have to be accompanied by a transfer of financial resources to the new partner(s).
- In general, attempts to lure experts from widening countries to resettle into the more advanced countries should be carefully scrutinized and not pursued should other solutions exist (e.g. preference to contract work, dual affiliation etc).

2.8.C: Environmental and social objectives

The United Nations' 17 Sustainable Development Goals (SDGs, also called the Global Goals), the European Green Deal, and EU next-generation funds are all initiatives aimed at developing peace and prosperity around the world. Among other things, the SDGs are meant to serve as guidelines for businesses to operate in a sustainable manner.

The potential of QT to change the world is enormous. It has the potential to significantly affect several economic sectors, such as telecommunications, national security, medicine, agriculture, and finance. One of the main topics of discussion on sustainability is the potential of QTs to reduce the energy required for complex computations, even as demand continues to increase. At the same time, the promising processing capabilities of QC could enable new scientific solutions to be used in improving healthcare and better environmental models, part of the UN SDGs, while also bringing benefits for industry, innovation, and infrastructure (Goal 9).

While there is this positive impact that QTs can have on society, QTs have also the challenge of being energy efficient themselves. Quantum technologies are just entering the economic sphere. As "deep techs", they are strongly coupled to fundamental research and rely a lot on public funding, such that there is flexibility on priority adjustments. Integrating the energetic dimension now is possible and will send a strong signal to society. It would ensure that science and technology stakeholders care about bringing out responsible innovations by developing conceptual tools and applying them to minimize the resource consumption and societal impact. It will make quantum technologies a model of virtuous deployment process for future innovations. This is essential in a world where resources are limited, and where the positive impact of science and technology for mankind must be demonstrated more than ever.
Implementing sustainability measures has several benefits for companies, and for society in general. This is encouraged by national regulatory bodies, and some governments are providing capital and tax benefits to those that invest in sustainable activities. Brand reputation is affected by how sustainable a company is, due to societal awareness of the topic. Last, but not least, major investors are also increasingly mindful of their portfolio companies' performance on SDGs. As quantum technologies move closer to providing quantum advantage in a range of industries, the governance bodies should lead efforts to enable companies to achieve environmental and social goals by identifying appropriate high-impact use cases.

As for any new technology, scaling existing quantum technologies to make it accessible for all will have an environmental and social impact. On the technical side, it is important to understand the energy cost of a quantum process, from both the fundamental and experimental sides (see section 2.4.D). This will allow energetic optimization of the hardware and protocols that will be used. However, mass production of quantum devices will raise sustainability issues such as finding the necessary resources, electronic waste or job creation and suppression. The well-known "rebound effect", i.e. the mechanism by which gains in the energetic efficiency of a technology tend to translate into more needs, increasing the global energetic consumption, is also bound to happen with quantum technologies. These issues should be studied before the industrialization of the field, for example by pushing research or initiatives on sustainable quantum technologies. Here are examples of open questions:

Around energy issues :

- What are the global energy cost's associated with deploying quantum technology (spanning; hardware,

middle ware and software operations) for the mainstream quantum technologies: computing, communications and sensing
- Is there an energy advantage of using quantum devices over classical devices?
- How can we limit the rebound effect of quantum technologies ?

Around infrastructures:

- What is the societal and environmental impact of adapting the existing Internet architecture to a quantum Internet? Is satellite-based communication a viable approach ?

Around impact on environment:

- What are the physical resources involved in quantum hardware? Can we responsibly find the resources for mass production of quantum devices ?
- What type of waste will be generated by the quantum industry? Can we reuse a quantum device?
- Can we use quantum technologies to fight climate change?
- How to connect the current research and scientific areas, initiatives, projects and communities working in enviromental and social challenges with quantum communities to allow cross-pollination of ideas, collaboration and projects?

Around industry and society:

- What is the impact of the new possibilities offered by quantum devices on other industries such as medical companies?
- What is the impact of widespread industrialization of quantum technologies on the job market?
- How to prioritize, guide companies and community effort and funding to make accessible quantum tech driven solution to accelerate SDGs goals and EU Green deal KPIs?
- How to apply quantum tech to accelerate the improvement of companies ESG scoring?

A new technology also induces new possibilities for human interactions which also impacts human behaviour. Since quantum mechanics challenge our conventional view of the world and present counter-intuitive results, thus making their comprehension from the general public much more difficult. These questions should also be addressed through continuous debunking operations on the quantum realm and popularization science.

- Specific call, governing boards and working groups with a dedicated budget to help answer (some of) these questions is needed in the short term as this will set up the basis for the research and development and positive impact of QTs of the future.

2.8.D: Ethical values

Emerging technologies have the power to disrupt society, and it is required to consider the societal implications of new technologies before they reach full maturity. Ethical concerns regarding quantum computing have been discussed and global ethical guidelines are beginning to be drawn up, with clear principles and approaches to mitigate the risks and unintended consequences from the outset.

The current development of quantum technologies is not only driven by the possible military applications of quantum technologies but is also inhabited by a broader atmosphere of international rivalry and tension that motivates people to take action. These assertions and recurring themes are familiar aspects of cultural stories surrounding novel technologies, often predicting and shaping future developments. Nevertheless, instead of merely replicating old patterns and clichés of the past, there might be alternative approaches to managing the advent of quantum technologies in a more innovative way.

Although quantum mechanics has been surrounded by an aura of mystery, it is important to recognize that users of quantum technologies should not be confined to a world of incomprehensibility. On the contrary, we need responsible and practical approaches to make quantum technologies familiar and accessible to the general public. In a similar vein, the broader implications of quantum theory should be applied to quantum information and quantum technologies. Once they become integrated into "normal" science, as Thomas Kuhn famously described, the mysterious element will diminish. However, it is crucial to preserve and rejuvenate the rich intellectual tradition associated with quantum mechanics. Without doing so, there is a risk that the cultural void will be filled with nonsensical and potentially dangerous pseudoscientific ideas.

It is commendable that some individuals in the field have prioritized public science communication and educational initiatives. However, it is important to emphasize that researchers and innovators, who rely on public funding and goodwill, must engage transparently with society. This engagement will help them understand public concerns and address social uncertainties. Merely proclaiming the disruptive potential of quantum technologies based on promises alone is not helpful. A clear and humble approach that acknowledges constraints as well as opportunities is often preferable to selling unsubstantiated hype.

While speculative visions play a vital role in guiding research and exploring unforeseen possibilities, enticing promises couched in the language of profit-driven ventures, particularly those promising quick returns in the quantum domain, carry the risk of backlash, dashed hopes, and hindered progress. In some cases, the financialization of futuristic promises may even stifle innovation, preventing technical breakthroughs before they can materialize. To be truly disruptive, quantum technologies should not be developed in a manner that simply perpetuates the status quo, replicating existing social conditions and unsustainable values into the quantum future.

Instead of framing the emergence of quantum technologies as just another technological revolution characterized by competition and superiority, we should consider alternative possibilities. Perhaps we can envision quantum technologies in terms of collaboration, and open science. However, this is easier said than done. If we strive for quantum technologies that uphold the values of transparency, fairness, and inclusivity, it will be necessary to develop new ways of discussing quantum resources that go beyond familiar tropes and prevent new technological advancements from perpetuating toxic historical patterns. By paying closer attention to the sociotechnical aspects of quantum technologies, we can make them less mysterious and more understandable to the public, while also making them less susceptible to established geopolitical agendas.

Inspired by the Towards a Different Spin[1] manifesto here are some practical recommendations around how Quantum Technologies should be, comprehensible, open, accessible, and meaningful, so that engages with a greater variety of societal needs, hopes, and concerns, steering the development of quantum technologies toward applications that are impactful for society at large.

We need to present quantum technologies in ways that are legible, honest, and publicly accountable, focusing on applications that may have particular advantages and disadvantages for different groups of stakeholders. In these times of mass information and misinformation, avoiding the blackboxing2 phenomena is necessary for the development of quantum technologies by explaining quantum technologies without any reference to the halo of mystery surrounding quantum theory.

- Avoid pseudo-science and engage our democratic societies in the questions surrounding the development of quantum technologies, pedagogy and research in quantum foundations are necessary.
- Pursue the research aiming at demystifying for physicists too, so that they can communicate on their work without mystifications.

We must work to make quantum technologies available to communities beyond early adopter states, start-ups and Big Tech companies. At the same time, we need to ensure accessibility, and enhance the diversity of the field's workforce, design implementations that anticipate and support the greatest variety of users and contexts, and ensure that countries of the Global South have access to applications of quantum technology that are relevant for meeting specific needs, mindful of any disparities that may widen gaps or exacerbate inequalities.

To ensure that QTs are responsible we need to involve sustainability research, technology assessment, and practices of responsible research and innovation to investigate possible long-term effects of quantum technologies, including unintended consequences, with an eye to the interests of future generations as much as our own.

In addition to quantum technologies addressing societal grand challenges, it is essential to also understand its application to everyday practices. The social purposes of potential users might be diverse when quantum technologies are ready to be adopted by the market with radical and unexpected innovations emerging. This may create a set of diverse affordances and constraints perceived by social actors and actualised as the use of QTs. Therefore, strategies for communicating about quantum technologies with the public are needed, to build trust in these new technologies and ensure benefits accrue to all parts of society in a responsible manner[4]. Scientists, policy-makers and communications experts should work together to create narratives around the usefulness of quantum technologies, focused on practical problems that can be solved. The intertwining between the properties of QTs and users' social intentions could overcome users' cognitive biases and facilitate ways of learning actions to perform their daily activities with QTs which could stimulate innovative practices. Thus, we must ensure that there are ongoing research and investigations to be led in the empirical field to understand social implications of QTs at micro-level usage and adoption.

The quantum community needs to learn from the current discussions around AI and the impact that this type of technology can have on society especially when it comes to inequalities and ethics[3]. Quantum technologists have a responsibility to learn from AI and other deep tech fields that are more evolved and to be proactive in anticipating the ways quantum may be misused to harm vulnerable communities. We must ensure quantum technology is designed and used for the greatest and most equitable public good.

It is important to take action now before it is too late or will require an exponentially larger effort as seen in fields such AI in which underlying ethics discussion arrived too late to substantially influence the culture of design in the field. Once QTs are further integrated in different sectors of society, in large infrastructures and investments both in the public and private spheres, efforts to regulate will be complicated by path dependency as well as pushback from the involved stakeholders as there might be required to make fundamental shifts to business practices. This highlights the urgency of bringing conversations about quantum ethics forward as soon as possible.

Recommendations

- Creation of a European Quantum Ethics Initiative and appropriate funding to conduct ethical research We should fund ethical research and discuss the matter of the development of quantum technologies before it is too late.
- Working group between EU quantum flagship and Europe Green deal KPIs initiatives, and EU moonshots mission
- Making fund resources available, to support the less access to quantum solutions to apply for their areas / countries (also add the management of these program / initiatives)
- Add recommendation for diversity and gender equality

2.8.E: Objectives and Recommendations

The following objectives and recommendations is a summary of individual objectives set in the sections above in detail. This provides a summary of those common to the various sections of the chapter.

Objectives and Recommendations:

- Clear map of use cases and impact of Quantum Computing against EU and national objectives in challenge areas
- In addition to mapping impact of quantum on challenge areas, investigate quantum advantage for these areas
- Engagement between scientists and policymakers and communication experts to be coherent on the above objectives
- Formation of a European Quantum Ethics Initiative to tackle these challenges
- Monitor and replicate other initiatives in ethical use of deep tech (e.g. AI)
- Widen access to quantum industry to resources which allow building of commercial products (e.g. information on IP and trade)

[1] Quantum Technologies and Society: Towards a Different Spin, C. Coenen, A. Grinbaum, A Grunwald, C. Milburn & P Vermaas, arXiv:2111.12442
[2] Pandora's hope: essays on the reality of science studies, Bruno Latour (1999), Cambridge, Massachusetts: Harvard University Press. p. 304.
[3] A Holistic Approach to Quantum Ethics Education, J.E. Arrow, S.E. Marsh & J. C. Meyer, arXiv:2306.00027
[4] How to introduce quantum computers without slowing economic growth, Velu, C. and F. Putra. (2023), Nature, 619, 461-464.

2.9

Communications and Outreach

2.9.A: High-level goals

Maintaining public support for European funding of quantum science and technology is crucial, and activities on communication and dissemination, as well as outreach are among the key aspects of this goal. Those actions should also inspire individuals to join the EU quantum workforce, by encouraging school and university students to discover quantum science and inducing graduates to pursue further training or jobs in the quantum industry. To do so, the stakeholders should share one strategic common vision for external and internal communication by reaching a consensus on the different stakes of communication in support of action. Those stakeholders are policy makers, industry, and academia leaders aware of the value of quantum innovation, technologies and research for future competitiveness and growth in Europe. They should clearly state the possibilities and limits of quantum technology for industry and society to ensure a realistic expectation of quantum research and a realistic assessment of the achievements of quantum technology research, innovation and commercialisation. Therefore, a strong collaboration and coordination within the Quantum Community Network should be encouraged to establish and institutionalise best practices on communication and make knowledge sharing a norm. European citizens must be included in this process to promote additional cooperation and investment and encourage their participation in accomplishing the target.

The relationship with the traditional media must be strengthen and new channels must be legitimate to reach wider audience. This way, information shared to the public is more accurate, aligned, and consistent, to avoid false rumours and expectations, mis- and disinformation.

2.9.B: Challenges

2.9.B.1 Political challenges

Communicating on EU policies, ethics, and measures in order to manage risks associated to introducing new quantum technologies in Europe requires to define policy guidelines. Attention grabbing and creative ways to bring the complex and technical contexts of political actions (e.g. Chips Act) closer to the stakeholders (especially industry and the general public) have to be taken into consideration. The communication at EU-level should not compete with those of national quantum technology programmes but be complementary.

Stakeholders should finally have in mind that quantum research is a complex, costly and long-term endeavour. As an example, the first "finished quantum computer" with all its economic and societal benefits will only be available in many years' time. The politicisation or extreme popularisation ("hype") of public communication about quantum technologies are risks that might lead to false information or unmatched expectations. Integrity risks are also imminent when popular ambassadors or champions of quantum innovations, technologies or research are linked to controversial, albeit unrelated, issues.

2.9.B.2 Financial challenges

Supporting and encouraging public funding, acceptability and utility to citizens is crucial. Budget for outreach/communication and dissemination activities is mostly an afterthought for projects, resulting in limited efforts to communicate to relevant actors properly and adequately. As for private funding, there are challenges linked to building more attractivity to invest in the potential of quantum tech and long-term impact projects and ideas. Moreover, medium-term interim results of long-term quantum research can be used at an early stage to upgrade or expand the product range of private investors.

2.9.B.3 Human resources challenge

The outstanding position of the US, China, and Japan as competitors in quantum research and industry reveals that quantum education needs to be strengthened in Europe. Public outreach is a key aspect to inspire young citizens' interest in quantum science, potentially leading to them pursuing a career in quantum technologies. Target-group-oriented information campaigns on site and online must address teachers so that schoolchildren can awake their fascination for quantum research at an early age, particularly for girls and young women.

Within the framework of ongoing research projects, participating academic institutions and industry must advertise their successes to date and job vacancies within the framework of information campaigns. An effort should be dedicated in communicating the broad range of options that students and graduates have regarding taking up jobs or studying in the quantum sector within Europe. An exchange of best practices between institutions considering the needs of widening countries should be developed.

Talent attraction and retention is key for any particular ecosystem, and in the emerging field of quantum technologies, additional funding and activities should start now to ensure the availability of the future workforce.

2.9.B.4 Dynamics

There is now no established group of communication professionals in the quantum industry. This issue makes efforts at capacity-building, knowledge-sharing, and networking more difficult. Having too much working groups divides the resources and dilutes the impact of communication activities while common and aligned messages and decisions are required. Despite the lack of resources to synchronize, a relatively compact discipline within Europe, allows taking advantage of the many overlaps of personnel within a wide variety of research projects. A European internal and external communication unit to help the European quantum sector, which is confronted with a heavy workload, to network, exchange information, define strategic goals and implement them should be established.
Until now mainly students and academics were the ones taking the lead on disseminating results and creating and deploying outreach activities. The support of other stakeholders (government, industry) is fundamental.
Finally, academically trained specialists from other research disciplines should be encouraged to enter the field of quantum communication management.

2.9.B.5 Societal challenges

Citizens should be aware of the positive economic and societal benefits of quantum technology. To do so a strong focus must be dedicated to explaining quantum technologies, their mode of operation, use cases and added value for society, as well as potential risks and opportunities. Bringing citizens into conversation with scientists and other quantum stakeholders is a reasonable mean to make them feel part of the process, eliminate fears and prejudices about deep-tech subjects and the impact on society. It is important to communicate the benefits and value of quantum technologies to the whole society. However, this means communication must be done for groups with very different initial knowledge of and interest in the topic. The different stakeholders, e.g. teachers, students, businesspeople, factory workers, must be identified and a communication strategy must be developed that addresses them and their interests, worries, hopes and level of knowledge. Honesty concerning the status of the technology is important, but even more important is to show a clear path towards practical applications of quantum technologies and the huge benefits they will bring to society.

2.9.C: Objective and Recommendations

Recommendations for 2023-2026 - action-related :

- Need to create a sustainable CSA continuing the same vision.
- Information campaigns on the above-mentioned topics for all stakeholders on social media, websites of projects and initiatives, public EU TV and radio stations in suitable editorial environments.
- Information events in schools, universities, at youth and job fairs, industry fairs and conferences.
- Establish a plan together with the Education and Workforce Development subcommittee for promoting quantum MSc programmes and other educational programmes and initiatives across Europe.
- Establish a platform to share resources and best practices in public outreach among all QCB members, complementing QTEdu one.
- Establish connections with communications/outreach officers within Europe's national quantum technology programmes.
- Need to be more present in international events business and science oriented as well as ones targeting the general public.
- Quantum Coordination Board sub-committee for outreach needs to grasp the necessity for a true coordination of efforts and establish joined concrete actions and goals. The QCB also needs to provide more support to tackle the communications need of resources to reach a larger audience.
- Statement of intent for procuring Quantum Services once available. Policy makers / politicians to publish a written statement of consent to procure quantum technology services (like e.g. QKD keys) once the technology is mature, certification is ready and networks are deployed.

Recommendations for 2027-2030 - strategic :

- Expand already existing QCB/Flagship communication structure (working group) (basically referring to this: Need to create a sustainable CSA continuing the same vision):
  - Establishment of a) European Staff Unit for Internal Quantum Communication to coordinate all political, academic and industrial stakeholders in the joint effort for communication and outreach in the field of quantum: management-focused.
  - Establishment of b) European Staff Unit for External Quantum Communication to coordinate and implement joint communication and outreach efforts of all stakeholders: communication-focused.
  - Recruitment campaign for members of both units mentioned above: Professionals and career switchers in the field of management and public relations for the European quantum infrastructure.
- Reserving an appropriate budget on EC level as well as on national Member States level for procurement of Quantum Services.

2.10

Governance

Europe boasts a rich history of successful collaboration across various domains, encompassing politics, economics, science, technology, and industry. The construction of the European Union stands as a testament to managing diversity and leveraging it as an asset. In contexts more comparable to the quantum realm, other instances have proven inspiring and have furnished valuable experiential insights into the governance of ambitious and intricate projects or organizations. Within the realm of science and technology, CERN, ESA, and ESO shine as exemplary instances of fruitful cooperation, positioning Europe as a global leader, if not the foremost one. In the industrial domain, in addition to space endeavours, Airbus also frequently garners attention as a paragon. Consequently, discussions about creating the "CERN of quantum" or the "Airbus of quantum" have been commonplace when designing the Flagship governance structure.

Indeed, the lessons derived from these ambitious undertakings, spanning institutional, scientific, technological, and industrial aspects, have contributed invaluable inputs to shaping a robust and sustainable ecosystem for quantum science and technology in Europe based upon effective governance and well-defined organization. The established Flagship's governance model has so far significantly contributed to the success and swift expansion of quantum technologies across the Union, by providing guidance for decision-making, ensuring optimal resource utilization, and assisting stakeholders in maximizing their contributions.

Given the anticipation of continuous evolution within the QT ecosystem, it becomes imperative to outline the guiding principles that have shaped and should continue to shape the architecture and development of the Flagship's governance for the years to come. As such, this section will first revisit fundamental principles governing large-scale initiatives, subsequently showing how they have been applied to the quantum realm. In particular, we will describe the current governance of the Quantum Flagship, shedding light on how the governance structure was built to adapt itself to the rapidly changing European landscape. Next, we will describe the evolution and growth of the European quantum ecosystem since the Flagship inception of 2018, aiming to provide recommendations that account for the expected evolution of the quantum landscape over the next years.

2.10.A: Governance principle

The governance structure, as exemplified by the one established for the Quantum Flagship (as described in the next section), has been built upon the following foundational principles:

- **Comprehensive Stakeholder Engagement:** Identifying all stakeholders and thoroughly analysing their roles, interests, and requirements.
- **Clear Role Allocation (RACI):** Defining distinct responsibilities for each stakeholder, ensuring a distinct separation of roles.
- **Project-Centric Implementation:** Executing programs through meticulously planned project-based approaches.
- **Proactive Risk Management:** Identifying and effectively managing potential risks throughout the entire governance process.
- **Ongoing Assessment and Review:** Regularly evaluating strategies and risk management through peer reviews.
- **Inclusive Decision-Making:** Striking a balance between top-down and bottom-up processes to facilitate inclusive decision-making.
- **Optimal Structure:** Equilibrating large representative boards with smaller operational committees or teams.

Additionally, two fundamental workflows are of paramount significance:

- **1. Appointing Processes:** This entails defining the procedure for appointing stakeholders or their representatives to specific roles within the governance framework.
- **2. Task Allocation:** Particularly crucial for risk mitigation, events management, and non-conformity resolution, this involves delineating various processes, assigning responsibilities, and ensuring stakeholders are held accountable for their actions.

These principles aim to ensure the active involvement of all stakeholders in decision-making, while structuring the project/program implementation to cater to the needs and concerns of all participants. Presented below is a schematic representation of a governance structure, clearly demarcating the "powers/responsibilities" among those responsible for proposing, evaluating, deciding, and executing.

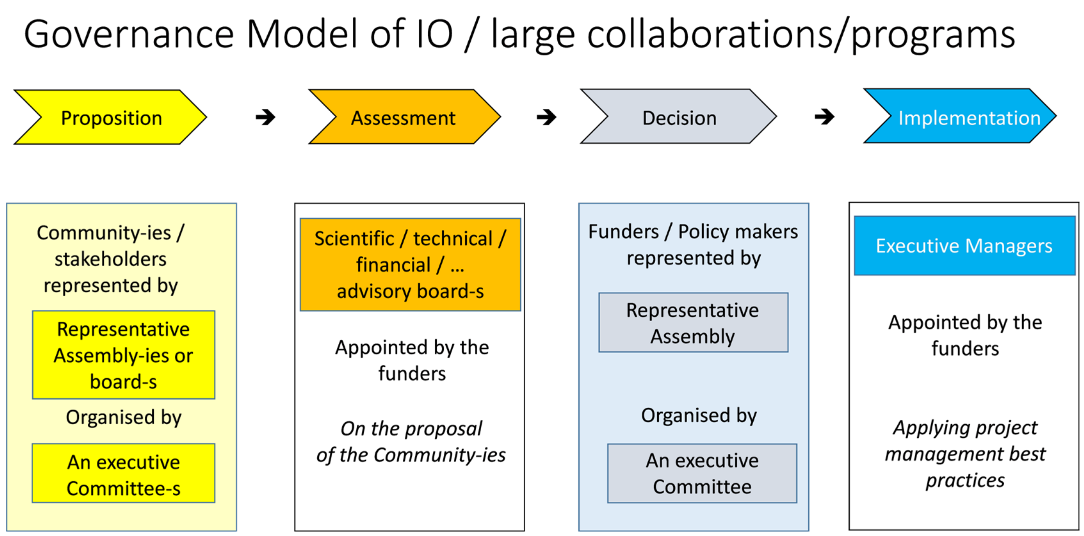

Figure 2.10.1: Governance model

These governance principles played and will play a pivotal role in ensuring the success and sustainability of the European quantum science and technology ecosystem. They empower the realization of its full potential by addressing key roles through the formulation and execution of a comprehensive strategy for its development:

- **1. Collaboration and Coordination:** Encouraging collaboration among research institutions, academia, industry, and governmental bodies to foster the exchange of strategies, resources, and knowledge.
- **2. Strategic Planning:** Formulating a collective strategic plan for the European quantum science and technology ecosystem encompassing goals, priorities, targets, and necessary resources.
- **3. Funding and Investment:** Providing a platform for discussions and negotiations on funding and investment to bolster quantum research, development, and commercialization activities. Ensuring equitable, transparent, and merit-based distribution of public funding.
- **4. Intellectual Property:** Safeguarding and upholding intellectual property rights.
- **5. Ethics and Regulation:** Ensuring responsible and secure conduct of quantum science and technology research and development.
- **6. Talent Development:** Supporting the cultivation and mobility of a diverse, skilled workforce within the EU to drive innovation and growth, including attracting and retaining talent, as well as promoting education and training in quantum science and technology.
- **7. Monitoring and Evaluation:** Continuously monitoring and evaluating the ecosystem's performance against set goals and objectives. This process identifies areas for enhancement and guides decision-making.

2.10.B: Current Quantum Flagship Governance structure

The current governance structure of the Quantum Flagship has been based on the principles exposed in the previous section, and comprises various bodies that collaborate to pursue the overarching objectives of the initiative, namely:

- Accelerate and propel the EU Quantum industry.
- Enhance EU's scientific leadership.
- Foster EU's appeal as a hub for innovative business and investments.
- Look for Quantum Technologies' potential in diverse domains (e.g., energy, health, security, and the environment).

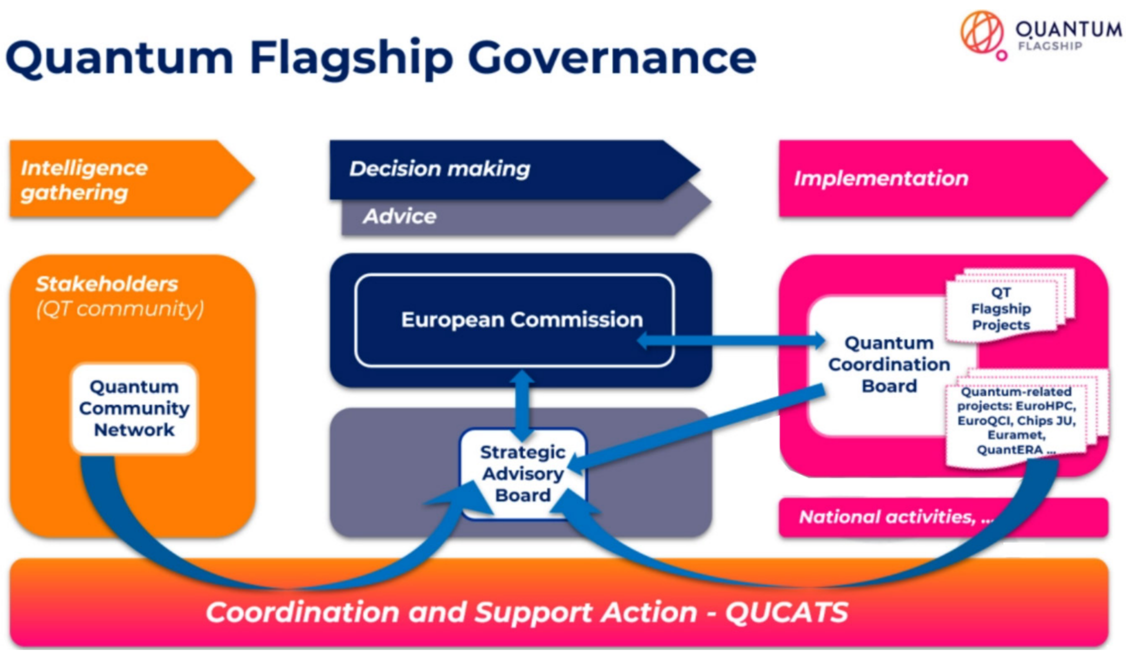

Figure 2.10.2: Quantum Flagship Governance

The existing Quantum Flagship governance structure is illustrated in the above figure. There are three distinct governing bodies, outlined in the following.

- **Strategic Advisory Board (SAB):** The Strategic Advisory Board (SAB) comprises eminent and respected independent quantum experts. Their role is overseeing the Quantum Flagship's progress and contributing insights to the Strategic Research and Industry Agenda (SRIA). They offer guidance on various matters to decision-making bodies. The composition of SAB includes 40% industry, 40% academia, and 20% Research and Technology Organizations (RTO).
- **Quantum Coordination Board (QCB):** The Quantum Coordination Board (QCB) is coordinating and aligning funding initiatives in QT initiated by the European Commission. It consists of the coordinators of all ongoing EC quantum projects. QCB's responsibilities encompass harmonizing Quantum Flagship Research and Innovation project activities,

identifying common themes, proposing unified solutions, and operating throughout the Quantum Flagship initiative's duration.

- **Quantum Community Network (QCN):** The Quantum Community Network (QCN) is representing the Quantum Technology communities of EU member states and associated states within the Quantum Flagship. It comprises one member and one deputy member per member state and associated state. These members are distinguished experts with substantial networks within their national quantum communities, formally appointed for the role. The primary objective is to synchronize the Flagship with national programs, engage and involve pertinent national stakeholders, and serve as the primary contacts for all Quantum Flagship-related inquiries within their respective countries.

A **Coordination and Support Action (CSA) – currently QUCATS (2022-2025),** is finally serving as the Quantum Flagship Secretariat. It assists the three governance bodies in their functions and organizes the engagement of quantum stakeholders. It also enlarge the Flagship scope by hosting different Working Groups on various topics, e.g., Equity, Diversity and Inclusion, Key Performance Indicators, and Standardization.

2.10.C: Evolution and growth of the European quantum ecosystem

The Flagship ramp-up phase has laid down a sturdy foundation for the second phase of the initiative. This new phase will sustain its commitment to advancing the most promising QT across different pillars, ushering in novel technologies such as photonic quantum computing, and continuing to advance the realm of quantum fundamental science, a pivotal force that has propelled the evolution of established quantum technologies and spawned concepts leading to original innovations.

Prompted by the Flagship's remarkable achievements, the European Quantum ecosystem has enormously expanded since the initiative inception in 2018.

The **Quantum Industry Consortium (QuIC)** was established with the objective of amplifying the competitive edge and economic expansion of the European quantum technology industry. QuIC's mission includes fostering value generation across the continent, while simultaneously fostering a robust EU ecosystem that encompasses Small and Medium-sized Enterprises (SMEs), major corporations, investors, and preeminent researchers.

Within the Horizon Europe and Digital Europe programs, two critical infrastructures have been launched and will be completed:

- The **European Quantum Communication Infrastructure (EuroQCI)** with the objective to construct a secure quantum communication framework that spans the entirety of the EU, encompassing its overseas territories.
- The **European Quantum Computing and Simulation Infrastructure (EuroQCS)** designed to integrate the quantum computers and simulators of the Flagship into the European Union's High Performance Computing (HPC) infrastructure that will play a key role in the future of HPC with post-exascale, energy-efficient computing technologies.

In addition, translating the outcomes of the Flagship into market-driven innovations requires supporting the development and manufacturing of quantum chips in particular to: enable miniaturization of quantum devices; facilitate their integration with other components, including control electronics and connectivity; enhance fabrication reliability for large-scale adoption and mass-market applications. This will be ensured by the **Chips for Europe Initiative**, which will complement the open testing, experimentation and pilot production capabilities for quantum technologies with advanced technology and engineering capacities for accelerating the innovative development of quantum chips providing quantum technologies' innovators with access to specialized clean rooms, prototyping and production foundries, as well as testing facilities to assess new components.

Additionally, in the last five years Europe saw the emergence of several **National Quantum Initiatives** dedicated to the development of Quantum Technologies, in Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Netherlands, Slovakia, Switzerland and UK. Significant resources have been committed for advancing all Flagship's verticals, as well as to the corresponding enabling sciences and technologies, training, and innovation. In Denmark and Sweden, similar initiatives have emerged funded by national private foundations. Overall, currently this corresponds to a total investment in excess of 5.7 billion Euro over a period of 5 years.

Other related activities include:

- A dedicated **European Innovation Council (EIC) Pathfinder Challenge.**
- The **QuantERA programme**, a network of 39 leading European Research Funding Organizations from 31 countries, supporting transnational research and innovation in quantum technologies.

Finally, further to these top-down initiatives, the QT community has also been very successful in finding support from major bottom-up funding opportunities, e.g. the **European Research Council (ERC), Marie Skłodowska-Curie Actions, and the European Metrology Programme for Innovation and Research (EMPIR)** which coordinates research projects to address grand challenges, while supporting and developing the SI system of measurement units

2.10.D: Adapting to the new QT landscape

Quantum sciences and technologies encompass a wide array of projects and initiatives, ranging from fundamental research to commercial services or product proposals, involving expansive platforms and maturation mechanisms. This landscape entails a multitude of stakeholders, spanning academia, industry, governmental agencies, state entities, current and prospective clients, as well as media involvement. This environment is undergoing rapid transformation. Member states continually unveil new facets of their quantum strategies, projects achieve significant milestones and publish findings, start-ups emerge and seek funding, while platforms introduce novel services and enhance their facilities. The European diversity, encompassing 27 member countries along with diverse funding agencies, research institutions, and industrial transfer structures, amplifies the intricacy and dynamism of the quantum landscape.

The diversity inherent in the European ecosystem serves as both a strength and a vulnerability. While it imbues Europe with creativity, adaptability, and responsiveness, at the same time, without effective coordination and governance, it can give rise to fragmentation and redundant efforts. This presents challenges concerning the attainment of critical mass and efficient collaboration; consequently, it might impede Europe from fulfilling its role in the global scientific, industrial, and economic arena.

The new array of initiatives reported above must now be thoughtfully integrated into the Flagship's governance structure. This integration must strike a delicate balance with the imperative for centralized coordination at the EU level. This becomes especially crucial given the Flagship's successful ramp-up phase that has catalysed the inception of substantial national endeavours, matching (e.g. Netherlands) or even surpassing (e.g.; France, Germany) the Flagship's funding.

No single nation possesses the capacity to single-handedly undertake the intricate task of quantum technology development. Therefore, all Member States must leverage the strengths of research and industrial entities spread across the Union. The necessity for robust EU-level coordination is further underscored by the presence of quantum pilot lines in the Chips Act. Indeed, EU coordination should ensure that whatever the origin or technology of the quantum device developed within EU they will be compatible with the standardized design and manufacturing processes of the European manufacturers that will be supported by the Chips Act.

National quantum programs alone would prove also inadequate to mature the design and manufacturing processes of quantum chips to a point of critical mass or sustainability. In this context, unifying and coordinating these initiatives under the Chips Act would engender scaling effects. This approach contrasts with dispersing resources into the formation of sub-critical players, and instead, drives synergistic growth and resource optimization.

Recommendations

- **The present governance structure is performing well** by international standards for large-scale initiatives. While the current SAB and QCN governance bodies do not need any major restructuring showing a satisfactory inclusivity and adaptability, the initial SEB has been successfully enlarged into a Quantum Coordination Board (QCB) to encompass all stakeholders and be able to represent the instances of the different projects converging towards QT applications. This transformation being recent it might be interesting to monitor its first year of existence to insure its complete success.
- For the future, evolutions and modification of the QT landscape such as new actors or programs should continue to be monitored and the governance of the European quantum ecosystem should continue to adapt it-self to include all stakeholders to maximize its growth and impact, it should.
- A **Coordination and Support Action should be always running** at any time during the whole duration of the Flagship initiative, to ensure sustained progress (QUCATS is currently slated to operate until 2025).
- **EU coordination should be strengthened** by creating:
- **A European Quantum Technologies MS Board**, bringing together all Member States with the Commission that will: coordinate National Quantum Initiatives; unite existing initiatives in quantum skills and training with the goal of developing quantum master's degrees across Europe, and a new quantum and industry education programme; discuss international cooperation matters with like-minded countries in areas of benefit for our EU interests, that would be based on reciprocity, a fair IPR sharing regime and open access to critical technologies.
- A **Top-Level Board**, involving half a dozen top-level representatives from the EU, the academia and industry supervising the realization of the ambitious scientific and industrial technology strategic agenda described in this document.
- There is scope for improving the quantum ecosystem's **connection with the civil society** beyond the actions already in place concerning education, outreach and communication. In particular, social and ethical concerns regarding QT start in fact emerging as the technology matures. One could think first about a Working group open to society which might then evolve into a specific link with civil society at the governance level.
  Additionally, fostering connections with other disciplines, especially Humanities and Social Sciences, at the research level can be explored to enrich the ecosystem's societal impact.
- As discussed in chapter on ethics, there is broader scope to identify impact of quantum on the United Nations' 17 sustainable development goals (SDGs)
- QuIC is in a position to shepherd this and should lead efforts to underpin QTs to enable companies to achieve their own environmental and social goals by identifying high-impact use cases

Glossary

Introduction

DG CNECT: Directorate-General for Communications Network, Content and Technology
EQTC: European Quantum Technology Conference
EU: European Union
HPC: High-Performance Computing
QCB: Quantum Coordination Board
QCN: Quantum Community Network
QT: Quantum Technologies
QuIC: Quantum Industry Consortium
SAB: Strategic Advisory Board
SIR: Strategic Industry Roadmap
SRA: Strategic Research Agenda
SRIA: Strategic Research and Industry Agenda
WG: Working Group

Quantum Computing & Simulation

API: Application Programming Interface
AQC: Adiabatic Quantum Computing
ASIC: Application-Specific Integrated Circuits
DSL: Domain Specific Language
EDA: Electronic Design Automation
EuroQCS : European Quantum Computation and Simulation Infrastructure
FTQC: Fault-Tolerant Quantum Computers
GKP: Gottesman Kitaev Preskill
HPC: High Performance Computing
HPC-QC: High Performance Computing – Quantum Computing
IC: Integrated Circuit
LNOI: Lithium Niobate On Insulator
MBQC: Measurement Based Quantum Computing
ML: Machine Learning
NISQ: Noisy Intermediate Scale Quantum
NV: Nitrogen Vacancy
PIC: Photonic Integrated Circuit
QA: Quantum Annealing
QAOA: Quantum Approximate Optimization Algorithm
QC: Quantum Computer
QC-PaaS: Quantum Computing Platform as a Service
QEC: Quantum Error Correction
QPU: Quantum Processing Unit
QS: Quantum Simulation
qSVM: quantum Support Vector Machine
SDK: Software Development Kit
SPD: Single Photon Detector
TWPA: Travelling Wave Parametric Amplifier
UHV: Ultra High Vacuum
VQE: Variational Quantum Eigensolver

Quantum Communication

EuroQCI : European Quantum Communication Infrastructure
ESA : European Space Agency
ETWG : EuroQCI Thematic Working Group
GeV : Germanium Vacancy
IRIS2: Infrastructure for Resilience, Interconnectivity and Security by Satellite
MDI : Measurement-Device Independent
NatQCI : National Quantum Communication Infrastructure
NV : Nitrogen Vacancy
PQC : Post-Quantum Cryptography
QEC: Quantum Error Correction
QKD : Quantum Key Distribution
QRNG : Quantum Random Number Generation
RTO : Research and Technology Organizations
SiV : Silicon Vacancy
SnV : Tin Vacancy
TF : Twin Field

Quantum Sensing and Metrology

AFM : Atomic Force Microscopy
CMOS : Complementary Metal-Oxide-Semiconductor
EMN-Q : European Metrology Network for Quantum Technologies
GNSS : Global Navigation Satellite Systems
IR : Infra-Red
JAWS : Josephson Arbitrary Waveform Synthesizers
JPVS : Josephson Programmable Voltage Standard
MEG : Magneto EncephaloGraphy
MEMS : Micro-ElectroMechanical System
MIT : Magnetic Induction Tomography
MRI : Magnetic Resonance Imaging
OPM : Optically Pumped Magnetometers
PDMR : Photo-electric Detection of the Magnetic Resonance
PNT : Positioning, Navigation and Timing
RF : Radio Frequency
SI : International System of units
SQL : Standard Quantum Limit
SNR : Signal to Noise Ratio
SNSPD : Superconducting Nanowire Single Photon Detector
SPAD : Single Photon Avalanche Diode
SWaP-C : Size, Weight and Power - Cost
VLBI : Very Long Baseline Interferometry

Transverse Chapters

EDI : Equality, Diversity and Inclusion
EIB : European Investment Bank
EIC : European Innovation Council
EIF : European Investment Fund
EPO : European Patent Office
EQRC : European Quantum Readiness Center
FCQT : Focus Group on Quantum Technologies
FPGA : Field Programmable Gate Array
GTC22: Joint Technical Committee
IEC : International Electro-technical Commission
IEEE : Institute of Electrical and Electronics Engineers
IP : Intellectual Property
ISO : International Organization for Standardization
ITU-T : International Telecommunication Union Telecommunication Standardization Sector
KPI : Key Performance Indicator
MS : Member State
NSB : National Standardization Bodies
PIC : Photonic Integrated Circuit
QTEdu : Quantum Technology Education
SDO : Standard Development Organisation
SDG : Sustainable Development Goals
SME : Small and Medium-sized Enterprises
STEM: Science, Technology, Engineering and Mathematics

QUANTUM FLAGSHIP