

**DRAFT**

**Strategic Research Agenda**

**(SRA)**

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Table of Contents

[Executive Summary 3](#_Toc15542970)

[Introduction 4](#_Toc15542971)

[Quantum Communication 9](#_Toc15542972)

[Socio-Economic Challenges 9](#_Toc15542973)

[Research and Innovation Challenges 10](#_Toc15542974)

[Roadmap 17](#_Toc15542975)

[Quantum Computation 18](#_Toc15542976)

[Socio-Economic Challenges 18](#_Toc15542977)

[Research and Innovation Challenges 18](#_Toc15542978)

[Roadmap 23](#_Toc15542979)

[Quantum Simulation 27](#_Toc15542980)

[Socio-Economic Challenges 28](#_Toc15542981)

[Research and Innovation Challenges 28](#_Toc15542982)

[Roadmap 31](#_Toc15542983)

[Quantum Sensing & Metrology 33](#_Toc15542984)

[Socio-Economic Challenges 34](#_Toc15542985)

[Research and Innovation Challenges 35](#_Toc15542986)

[Roadmap 37](#_Toc15542987)

[Scientific and Technological Resources 39](#_Toc15542988)

[Scientific Resources 39](#_Toc15542989)

[Technological Resources 41](#_Toc15542990)

[Roadmap 43](#_Toc15542991)

[Innovation 44](#_Toc15542992)

[Challenges and needs for developing new products and services based on quantum technology 44](#_Toc15542993)

[Infrastructure and supply chain 44](#_Toc15542994)

[Trained and Educated Workforce and Users 46](#_Toc15542995)

[Supporting and promoting the development of new products and services 46](#_Toc15542996)

[Innovation Roadmap 47](#_Toc15542997)

[International cooperation 48](#_Toc15542998)

[QT a major disruptive sector calling for a worldwide research and innovation 48](#_Toc15542999)

[A clear framework to benefit from international collaboration 48](#_Toc15543000)

[International collaborations in education and training 49](#_Toc15543001)

[Addressing the IP issue: Making Europe stronger to benefit from an open world 50](#_Toc15543002)

[Gender Equality 53](#_Toc15543003)

[The leaky pipe challenge 53](#_Toc15543004)

[Approach to gender equality in the Quantum Flagship 54](#_Toc15543005)

[Conclusion 55](#_Toc15543006)

[Gender Equality Roadmap 55](#_Toc15543007)

[Education and Training 57](#_Toc15543008)

[Current Status 57](#_Toc15543009)

[Planned measures 58](#_Toc15543010)

[Conclusion 60](#_Toc15543011)

Executive Summary

**To be completed.**

Introduction

**The introduction has deliberately not yet been published here. The introduction neutrally outlines the importance of Quantum Technology and the role of the Quantum Flagship as well as the process of SRA creation. We look forward to receiving feedback on the following technical chapters of the document.**

Quantum Communication

Quantum communication involves the generation and use of quantum states and resources for communication protocols in order to bring radically new applications to European citizen. Typically, these protocols are built on quantum random number generators (QRNG) for secret keys and quantum key distribution (QKD) for their secure distribution in cryptographic applications. Currently, the main focus is on provably secure communication and long-term secure storage as well as other cryptography-related tasks.

Quantum communication is already a reality today at distances of several hundred kilometres for simple applications like QKD, for which commercial products exist that can provide quantum secure communication at short distances. However, the same fundamental properties of quantum information which are responsible for providing unparalleled security, also prevent qubits from being sent over long distances using conventional repeaters. Instead, quantum repeaters are needed which are capable of transmitting qubits over long distances and enable end-to-end secure communication. Here, a combination of fibre- and satellite-based transmission can reach global distances. Space-based secure communication will be a crucial element for reaching planetary scales and beyond. It will provide a means for reaching global distances and secure space assets.

As an intermediary step, trusted-node repeaters have been deployed to bridge longer distances. Here, a larger distance is divided into shorter segments which do not have a quantum connection between them. Trusted-node repeaters can be used for QKD, however, while the building blocks for fully quantum repeater schemes have already been demonstrated in the lab, years of R&D are still needed for them to reach the market. As soon as this happens, true internet-wide quantum-safe security could become a reality.

The long-term vision is to develop a Europe-wide quantum network that complements and expands on current digital infrastructure, laying the foundations for a quantum internet. To achieve this, the objective is to advance quantum communications in three essential directions:

1. Functionality: Capitalise on the full set of applications quantum communication has to offer by building technology capable of applications beyond QKD.
2. Accessibility: Bring the technology to a large set of users as early as possible, by advancing the component and system technologies and developing a robust quantum technology supply chain.
3. Distance: Enable the generation of entanglement over long distances, thereby enabling end-to-end secure communication across Europe and globally.

Socio-Economic Challenges

The near- to medium-term applications of quantum communications are expected to be in cryptography, where it can be used to generate high entropy random numbers and to distribute secret digital keys, as well as perform several other important primitives. In the longer term, we may see application to communication between sensor and clock networks, as well as in distributed quantum computing architectures.

Quantum cryptography provides protocols whose security can be proven directly from information-theoretic principles and the laws of quantum mechanics, and which do not require any assumptions about the computational resources available to an adversary. Information-theoretic security will be important for data confidentiality in the future when we can expect more powerful computers and new algorithms to be at the fingertips of our digital foes. Of particular concern is the advent of quantum computer that can be used to launch efficient attacks on conventional techniques, such as the Diffie-Hellman key exchange algorithm.

The main challenge that quantum communication-based technologies may face at the current stage of development is the lack of access to the appropriate economic and human resources. The amount of investment needed to develop both the infrastructure that will allow the deployment of these technologies, and the development of new components that will unlock the full potential of a quantum internet is vast. There will, however, be a direct benefit to the European economy, delivered by the multi-billion € business for quantum cryptography expected to develop over the next decade. Several studies have predicted sales of quantum key distribution systems and services to grow strongly. The Institute for Quantum Computing (IQC) in Waterloo (Canada) have predicted the market to grow from about 30 M$ in 2014 to about 25 B$ by 2030. A more recent study from the Communications Industry Researchers Inc. in 2017 predicts the quantum encryption market will reach 15 B$ in 2026. Indeed, a robust and secure communication infrastructure based on quantum security will be essential for the whole European economy. It will benefit a wide range of users in the financial, healthcare, government and corporate sectors, and underpin many millions of jobs across Europe.

A significant challenge to this end is to ensure the engagement of existing European quantum communication industry partners, enable new-comers and the emerging start-ups, as well as facilitate the development and growth for QKD network services, related software, system integration and certification services, as well as for the supply chain of associated quantum photonic components.

To ensure the development of new technologies and systems, innovation platforms that enable innovators to develop new products and solutions are needed. The launch of the QKD testbed and possibility of a Quantum Communication Infrastructure could constitute the ideal testing-ground where innovators (e.g. software developers, hardware industry, internet service industry, security professionals) can get access to technology-testing, where new standards, procedures, protocols and security policies can be examined and tested, and it can serve as a platform where the quantum and the conventional communication communities can find a common ground. Enabling an open innovation ecosystem will allow for spin-off developments that will bring applications that may not yet be envisioned. There is also a need to ensure the European working force will have adequate skills to exploit these new technologies. This would facilitate the technology adoption by a broader sector of society.

Some challenges in this area are the protection of critical infrastructure, such as energy services, service networks, security of data transmission between remote industrial and/or chemical plants, security of smart living environments in smart cities of the future. Quantum-safe cryptographic solutions for infrastructure represents a major challenge to the resilience of services and needs to be addressed in a holistic manner, by combining adapted solutions including QKD. To enhance the autonomy and security of a digital Europe and to strengthen trust, we need to raise awareness about this issue. There are also implications for the security of financial transactions as well as long-term security of health records and the uptake of e-government and e-services. The extension of such platforms to genuine global-scale networks through quantum repeaters and ground-to-satellite quantum communication will enhance the societal impact of quantum communication technologies and help maintain European information security infrastructures in the quantum era

Research and Innovation Challenges

The future of Europe’s digital infrastructure will require the incorporation of quantum-safe solutions to ensure its integrity faced with the risks to modern cryptographic systems presented by the advances in quantum computing. This digital infrastructure can also take advantage of new functionalities afforded by emerging quantum technologies to connect small quantum processors, or sensor and clock networks, using photonic links and entanglement. To keep pace with this, there is a need to ensure a robust and sustainable supply chain of both people and technologies to build a European quantum industry. The following challenges need to be addressed to ensure a strong quantum future for Europe.

1. **Quantum Security** The privacy, security and integrity of data, at rest and in transit, as well as quantum-secure access to it, is an essential part of the strategic vision for Europe and quantum technologies need to be an integral part of this and its subsequent development.
2. **Entanglement-based Quantum Networks** The advantage provided by the distribution of quantum resources such as entanglement have the potential to provide improved and novel solutions to quantum security and new functionalities to complement the next generation of networks. Support for these longer-term endeavours is needed to expand the application potential for quantum communication.
3. **Supply Chain** To grow a dynamic and robust European quantum industry there is a need to invest, both in people and technologies. Investment in new concepts and component development, ranging from basic science to engineering is essential to build the necessary innovation ecosystem. This needs to be complemented by education and training programmes to ensure a quantum aware workforce from academia to industry and decision makers. The development of applications, protocols and quantum software also of paramount importance.

1) Quantum Security

Quantum technologies for ensuring the security of Europe’s digital infrastructure have seen enormous progress in recent years. Quantum key distribution (QKD) schemes have been commercialised for some time already but we are now seeing new start-ups arriving, significant advances in rates and distances that can be addressed, as well as in protocols that bridge the gap to quantum repeater-based QKD. Quantum random number generators (QRNG) provide not only the initial randomness to generate these secret keys, but play their own role in various cryptographic applications for PINs, the Internet of Things (IoT), securing critical infrastructure and long-term secure storage of medical records. They also have a much wider range of applications, from gaming to high-performance computing.

Work has already started on developing quantum communication infrastructures to test and demonstrate these technologies in real-world settings and where use cases and business models can be tested and validated. This will provide a setting in which to further develop end-user-driven applications and ensure their end-to-end security by integrating full hardware and software stacks, e.g. for key management and connection to the final user application. It will also provide a test-bed extending from metropolitan to pan-European and even global quantum secure solutions, by incorporating trusted node networks - a daisy-chain of QKD system - to go beyond the current demonstrations of 400km in fibre networks. While there are new protocols that hold the promise of going even beyond 500km, reaching distances of 1000s of km will require quantum repeaters (see Quantum Networks) or combinations of free-space-connected drones, high-altitude platform stations (HAPS), and satellites.

Achieving these goals will require facing a number of non-trivial challenges, needing very strong interaction between fundamental and applied research as well as quantum and conventional cryptographers. Beyond quantum-secure storage of data and transmission of data, the authentication of users accessing communication systems has to be made quantum-secure as well. Providing such end-to-end security, requires both the development of quantum-secure authentication hardware as well as software applications and protocols, to replace classical access methods, like pin codes or passwords, which are vulnerable against quantum attacks.

**Quantum Random Number Generation** (QRNG) is one of the most fascinating and practical quantum technologies, with diverse applications in cryptography, electronic gaming and numerical simulations. Given the pervasiveness of the deployment of random numbers, poor quality generators can be economically very damaging. As quantum physics provides the only true source of randomness in nature, it can provide a very attractive solution for the generation of random bit streams. It is very likely therefore that QRNG will be exploited in the first applications of quantum technology realised by the programme.

It is envisaged that a variety of quantum approaches will be deployed in different scenarios. For example, high security cryptographic applications, numerical simulation and modelling will require high-rate, high-quality QRNG, while for IoT or mobile phone applications, low cost, size, weight and power will be the main considerations.

A few quantum random number generators are already available commercially. However, they deliver relatively low bit rates (of order a few Mb/s) and are relatively expensive compared to competing non-quantum approaches. Fortunately, new schemes are emerging from the lab that can offer much higher bit rates in the Gbps regime. The generation of high-quality random numbers relies also on the theoretical techniques needed to extract and verify quantum randomness from the raw bit stream, as well as the ability to implement these on different platforms. Furthermore, integrated photonics will provide a route to significantly reduce the cost of QRNG in the future.

Looking to the longer term, device-independent QRNG and its many variants, look to overcome some of the security challenges of implementation and can provide a route for the self-testing of devices, which may also help with some of the quantum-specific certification. Further theoretical and experimental research is required to improve the efficiency of these device-independent schemes.

There are also many engineering challenges to be addressed to develop useful QRNG devices. Not least are the system integration aspects that allow QRNGs to be integrated seamlessly into IT systems.

Realising the full economic and societal benefit of QRNG will require Europe to establish a process for security evaluation and certification of devices, as this is essential for their use in many cryptographic applications.

**Quantum Key Distribution** (QKD) offers a provably secure way to establish a secret key between distant parties, which can subsequently be used in various cryptographic applications.

The past decade has seen increasingly impressive demonstrations of fibre optic based quantum key distribution, as well as the first demonstration of QKD between a ground station and a low earth orbit satellite. Despite this progress, there remain a number of scientific and engineering challenges to be overcome before QKD can make a wide-ranging impact on everyday life. The challenges, described below, may be summarised as reducing cost, improving performance, integration with current systems, establishing a certification processes for quantum security devices and developing new techniques and protocols, which can expand the current functionality.

One of the central challenges for both fibre and free space QKD systems is to lower the cost of the technology. This might be achieved by using new innovative designs that simplify the system, or by exploiting photonic integrated systems, where systems may be mass-manufactured cheaply on a semiconductor wafer. Chip-based QKD can also drastically reduce the size, weight and power requirements, which is important for many free-space applications, including satellites, and can enable new deployment scenarios such as in IoT.

Secure key rates may be improved through higher clock rates, more efficient components or protocols or by multiplexing multiple quantum channels in parallel. This is important for both fibre optic systems where network deployment results in the secure rate being shared between many users, and for satellite QKD for which optical losses tend to be high.

Another important challenge is to extend the distance of a secure QKD link. Current technology allows fibre links of a few hundred kms using practical thermo-electrically cooled semiconductor detectors and up to 400km with low temperature superconducting detectors. Improvement in detector technologies are required to further extend the range of practical systems, as are the development and implementation of new protocols that can allow operation over 500km and beyond. Research on quantum relays and repeaters, discussed in more detail below, may eventually allow communication over longer distances. For satellite QKD, operation should be extended from low earth orbit to high earth orbit, as well as QKD between deployed satellites.

Ultimately QKD should operate as a component within a secure system, such as a secure communication infrastructure used in telecommunications or critical infrastructure. Realising fully integrated solutions that can operate in appropriate environments reliably is a considerable engineering challenge. Satellite based QKD systems present particularly extreme re-engineering challenges to cope with being launched into space and operating there.

Another important challenge to be addressed is the integration of quantum and algorithmic techniques to realise complete cryptographic solutions. This may include the combination of QKD and QRNG with other algorithm-based methods of quantum safe cryptography. Although the resulting composites may not be information theoretic secure, they may still provide long term security advantages over current methods. Collaboration between quantum and classical cryptographers should be encouraged to stimulate new quantum-safe applications.

The security of all cryptographic systems is based on a set of working assumptions. The unique feature of quantum cryptography is that none of these assumptions apply to the capabilities of an adversary. This is a highly desirable feature as assumptions about the adversary are difficult to test and impossible to control. On the other hand, the security of QKD does rely on the assumptions made about the QKD equipment and, in particular, how closely a real system implements the theoretical model. Research on the security of implemented systems (both fibre and free-space), including methods of attacking QKD systems and how to prevent such attacks, is therefore very important. This should be used to establish a third-party security evaluation and certification process for QKD equipment in Europe.

Device-independent (DI) QKD is an alternative approach to implementation security using verification procedures which are independent of the device and its implementation. Some notable examples are measurement-device-independent (MDI) and detector-device-independent schemes that overcome attacks and manipulation of the QKD system’s detectors, as well as the Twin-Field (TF) approach that combines aspects of MDI with the possibility of extending the point-to-point QKD distance. Although very promising, more research is required on protocols that can be implemented practically. Another avenue of investigation is to develop theoretical tools to handle a wider variety of DI-inspired protocols or better suited Bell tests, going beyond what has been demonstrated in laboratory settings.

**Quantum Networks** allow any-to-any connectivity amongst a large set of users, the flexible addition of new parties, as well as the extension of the point-to-point communication distance.

Most of the QKD networks realised to date have been distinct from the conventional telecom network and deployed on dark fibre carrying no other signals. For low cost deployment, it is important that quantum communication signals can co-exist with conventional traffic on data carrying fibres. More work is required on different schemes for multiplexing quantum and classical signals onto common fibre, as well as deployment on typical telecom architectures, such as point-to-point and point-to-multipoint links and with typical network components such as optical amplifiers and network switches.

Realising a network for key distribution requires the development of a protocol stack for generation, routing and storage of key material. More research is required on different approaches to quantum networking, and, in particular, for efficient implementation of large-scale networks. There should also be an investigation of how QKD may be implemented in a dynamic software-defined network. Collaboration between quantum and conventional cryptographers will be important to ensure the overall system security.

Current QKD networks work under the assumption that an adversary is unable to access the intermediate nodes, as well as the end points. Although eventually quantum repeaters (discussed below) may allow this assumption to be relaxed, practical deployments require investigation of how classical techniques (such as secret sharing) may be used to reduce the need for trust in the intermediate nodes. Practical implementations of MDI-QKD and TF-QKD will allow network deployments in which some of the nodes can be placed in untrusted locations and provide insight into the challenges faced for fully entanglement-based networks.

Quantum networks may also be extended using satellite QKD links to connect different metropolitan areas together. Some of the challenges to be addressed include increasing performance, operation during daylight and bad weather, the development of cost-effective ground stations and the interfacing of ground stations and fibre optic networks.

To date quantum cryptography has focussed mainly upon random number generation and key distribution. Although these are important techniques, from which many other cryptographic tasks can be derived, there should be more research to discover new quantum crypto primitives, especially in a network context, as well as experimental work on implementations. Examples include digital signatures, bit commitment, position-based cryptography and ever-lasting secure storage, for example in securing health records over human lifetimes (around 1 century). These all require quantum and classical cryptographic techniques, as well as close collaboration with network engineers, system operators and end-users to ensure end-to-end security.

Europe must take the lead in developing standards for quantum networks by utilising the QKD Industry Specification Group in ETSI. This is essential for ensuring interoperability of different components within a quantum network, which is important for stimulating the market, as well as ensuring that networks are implemented securely.

2) Entanglement-based Quantum Networks

The objective of realising quantum networks is to go beyond short distance QKD links, and expand the potential of quantum communication. Here the focus lies mainly on the first two challenges of realizing quantum communication, namely to increase distances, and enable advanced application functionality for the end-user. However, many key elements developed for Quantum Security which improve accessibility (specifically, low loss switches or cheap photonic clients) also form key ingredients for large scale quantum networks.

Quantum networks that create end-to-end entanglement offer advantages beyond those provided by trusted-node-based QKD networks. For quantum key distribution, they remove the need for trust at the intermediate nodes, and hence offer end-to-end security which is desirable in the latter phases of the European Quantum Communication Infrastructure. Moreover, such networks unlock a host of other applications in the domain of security, metrology, sensing, distributed systems, and even access to a remote quantum computer in the cloud, which will enable blind quantum computation.

On a high level, realising a fully-fledged quantum network requires advances in several key technologies in an interdisciplinary effort between physics, computer science and engineering. First, a quantum repeater is needed in order to ultimately produce entanglement over arbitrary distances. Several candidate technologies (and hybrids thereof) exist for such repeaters ranging from multiplexed quantum repeaters using quantum memories (e.g. systems using quantum memories based on rare earth memories and atomic gases), repeaters which hope to ultimately create highly entangled cluster states to send information by forward error correction (e.g. using quantum dots), to quantum processing nodes, which next to storing quantum information, also function as quantum computers (e.g. Nitrogen Vacancy (NV) centres in diamond, Ion Traps or Neutral Atoms).

**Quantum Repeaters** for long-distance communication (hundreds to thousands of kilometres), and in the quest for higher bit rates (leading ultimately to deterministic entanglement distribution), several scientific as well as technological gaps have to be filled. This effort spans from fundamental research to pure engineering challenges and can build on the trusted-node networks that are already taking shape. While still being at an early TRL, quantum repeater technology, including quantum memories for light, quantum light sources, detectors and interfaces between light emitted from different sources, have over the past decade moved from theory to a wide range of proof-of-principle demonstrations with encouraging results for the future that may be needed to develop a fully-fledged quantum network that will allow secure multipartite communication over long distances. Two approaches are explored to implement such a network, the first one, based on quantum memories (e.g. rare earth memories, atomic gases), and more recent approaches based on large photonic entangled states for forward error-correction (e.g. using quantum dots).

**End-Nodes** that connect to a quantum network, and on which applications are executed, can range from simple photonic devices as in QKD, quantum processing nodes using noisy qubits, to fully fledged quantum computers with an optical interface (e.g. NV in diamond, Ion Traps, Neutral Atoms) in a series of intermediary stages, where each stage unlocks further applications that can be run on such networks. We also need to interface end nodes and quantum repeater systems to enable maximum utility of the network. This requires hybrid systems linking quantum sources, or repeaters with performance significantly greater than the current state of the art with various quantum processing devices.

**Enabling Technologies** from a hardware perspective several key enabling technologies will be also required such as more efficient conversion to telecom wavelengths, low-loss optical switches, and enabling technologies such as robust phase stabilisation.

**Network architectures and control plane** Due to fundamental differences between classical and quantum communication, as well as technological considerations such as the limited lifetime of quantum memories, we also need a fast and reactive control plane in order to scale such networks. This calls for resilient protocols and architectures that can combat errors in practice, as well as the development of a flexible quantum network stack that orchestrates the interplay between applications and hardware. Such a stack for entanglement-based schemes has very different requirements than trusted-node-based quantum networks. A first such stack and early control protocols have recently been suggested in Europe, showing great promise to determine efficient control of large networks in the future led by European technology.

**Software stacks** are essential to ensure users can run present and future applications in an easy manner on such a network. This includes the development of a software stack for programming such networks, to run next to QKD as well as other applications on platform independent software. Importantly, for new applications, they will need to determine precise requirements for feeding in to the design process of early networks to be deployed.

Advancing quantum networks, requires an extensive long-term and focused engineering effort in synergy with advancements in physics and computer science. To ensure the development of these new technologies and systems, platforms that enable innovators to develop and test new products and solutions are needed. The software industry could benefit from these testbeds by being able to develop new products without the need to invest in (very costly) quantum hardware and fibre infrastructure themselves. The hardware industry could also establish interoperability between different physical systems and platforms.

3. Supply Chain

The issues of scale, range, reliability, and robustness that are critical for quantum communication technologies cannot be resolved by incremental improvements, but rather need to be addressed by making them the focal point of the strategic research agenda. In addition, the final solutions are far from known, and a large variety of possible approaches and technologies are presently pursued in parallel. As such, it is essential to perform an extensive requirements study, and significantly advance performance of all enabling technologies underlying quantum communication technologies.

As appropriate for the requirements of quantum network systems, this study can include a targeted advancement of supply chain components including light sources, interfaces, quantum memories, and detectors, while making sure that they are compatible and can work together. This includes making classical support technology—stable lasers, cryogenics, etc.—cheaper, smaller, more robust and more user friendly, which will also benefit non-quantum applications based on the same devices and hence boost Europe’s competitiveness in non-quantum technology. The development of materials, fabrication and packaging solutions, are also key challenges, as is the development of new protocols, applications and software. All aspects of the supply chain components need to be studied, ranging from fundamental properties to engineering quantum devices and systems to interfacing these with integrated photonics, fast (classical) opto-electrical and FPGA systems, always with a view towards end-user applications and their operation in communication networks.

Central supply chain components for quantum communications include the following.

**Photon Sources** are key enabling technologies with important properties including wavelength, bandwidth, as well as purity and efficiency, which characterise the brightness of the source and its usefulness for coupling of the generated light into other systems. A range of directions that span different technologies and theoretical approaches need to be considered for various applications, including probabilistic, heralded or deterministic source operation; generation of single photon states, entangled photon pairs, and multi-photon entangled states such as graph states; encoding in discrete or continuous variables of light; chip-based techniques for scaling up quantum photonic sources. Approaches to engineer the generated states of light and to maximise the amount of information carried by the single or entangled photons will be useful for future quantum communication networks.

**Quantum Memories, Interfaces (and Switches)** typically involving light-matter coupling and provide an interface between quantum information carriers (quantum states of light) and quantum information storage and processing devices (atoms, ions, solid state systems). They are an integral part of a full-scale quantum information system. Improving the efficient interconversion between flying and stationary quantum systems, and interfacing with other physical systems, or other bandwidth regimes, will be crucial for advanced quantum networks.

**Photon Detection** technologies need further improvements in single photon detection efficiency in conjunction with lower dark count rates, smaller timing jitter and higher detection rates. For continuous-variable systems, developing coherent receivers with properties compatible with high-speed operation in the quantum regime is necessary. It is increasingly important to maximise performance for all parameters in one device, nonetheless devices optimised for specific applications or operating conditions—e.g. cryogenic or room-temperature operation, on the ground or within a satellite—should be considered. Size and cost need to be addressed with relevance to the target applications.

**Applications, Protocols and Software** will be key ingredients for secure and multi-functional quantum networks. The required developments are manifold. An advanced security analysis is required for new quantum communication protocols, including for instance continuous-variable QKD with discrete modulation, protocols exploiting relativistic effects, or QKD protocols exploring different photonic degrees-of-freedom (frequency, time bins, polarisation, path, orbital angular momentum), with the prospect of enabling affordable and practical services, well integrated into current networks and providing the highest security guarantees. In all such cases of protocol development, it will be necessary to set concrete security benchmarks and take into account realistic devices. In addition, a network stack with sufficient flexibility to deal with a large number of applications, network topologies, and hardware components has to be developed. This also includes appropriate interfaces between ground and space networks. Furthermore, classical cryptographic protocols and functionalities need to be incorporated into the larger quantum internet framework. Just like for computing, applications and use-cases need to be developed in close cooperation between industry and academia. As in the classical ICT field, quantum software developments can be expected to become much richer and more dynamic in the long run, enabling an extended quantum software supply chain.

**A Comprehensive Technological Environment** will be crucial for putting in place a sustainable supply chain for quantum communications. Research and development are needed in interdisciplinary topics. These include the development of high-rate QKD satellite payloads, space compatible components, advanced pointing and tracking systems, low-loss space-to-ground and inter-satellite links using adaptive optics, high bandwidth electronics, advanced data processing, optical devices such efficient, low-loss, modulators, low linewidth, stable lasers, and cryogenics. Scaling up quantum photonics will also require facilitating access to state-of-the-art foundry and packaging services and accelerating the runtimes for efficient and cost-effective system characterisation. Furthermore, access to optical ground stations will be necessary for developing space-based networks.

In addition to the developments required for forming the technological basis of the quantum communication supply chain, it will also be crucial to develop related education and training, as for all quantum technologies but with a special focus for such applications.

**Education and training** can be taught independently of the underlying atomic physics and electromagnetism. The concept of a qubit can be explained to high school pupils with modern didactic methods. With this, they can understand QRNG and simple QKD protocols, which in turn helps in the long run to establish quantum communication as common knowledge. This will increase trust of the society in this technology.

For the integration of QKD systems into optical transport networks, an important goal is to make QKD systems more mature and accessible to network technicians. Then, they can be introduced to network operators as “normal” optical devices with some special properties such as the use of very weak light only or more advanced receivers. This supports the acceptance of the technology on a technical level by technicians without quantum technology background.

Quantum communication offers many education opportunities in interdisciplinary topics, including theoretical and experimental quantum physics, space engineering, and cryptography and security. Hackathon types of events for the development of quantum internet protocols are also a means of popularising these concepts among students and practitioners.

Roadmap

The long-term success of quantum communication is reliant on pursuing both the immediate need for commercial ready QRNGs and QKD systems and demonstrating their operation in real-world networks, but also for the next generation of devices and systems for a quantum-safe European digital infrastructure.

**3 year vision:** We require standards (even for low TRL devices and systems) as well as certification methodologies for QRNG, QKD. The development of use-cases and business models, as well as cost-effective and scalable devices and systems for inter-city and intra-city, and in the context of a quantum communication infrastructure ((QCI), uptake in a substantial number of Member States. Demonstrate protocols for the security of long-lived systems and secret sharing exploiting quantum and classical cryptographic techniques. The demonstration of a protocol execution over an elementary quantum repeater link using an integrated control plane and platform independent software stack is an important milestone, as are the demonstration of key critical components for satellite based communication. A coordinated action at ESA/EU level for the components required for development of satellite QKD and preparatory actions for standardised QKD satellites and ground station components is needed. In parallel there is a need for software stacks, including key management and application interface, for end-to-end security. We should also see improved device performance addressing parameter benchmarks of relevance for cryptography and network applications, ideally exploiting a standardised test suite for various applications, protocols, and software. There is also a need to engage with other fields and stakeholders, such as EURAMET, ETSI, CEN-CENELEC, DIN, as well as classical cryptographers, network engineers, fabrication and packaging facilities.

**6-10 year vision:** Advances QKD and QRNG systems should demonstrate readiness for critical infrastructure, IoT and 5G. Trusted-node network functionality and interoperability for fibre, free-space and satellite links. End-to-end security over trusted nodes and eventually using repeaters between EU countries. Importantly, this may require the establishment of bi- or multi-lateral agreements between countries. The integration of at least 3 physically distant quantum repeaters over telecom fibre demonstrating key generation over more that 500km represents a major objective. Demonstrations of entanglement-based network application and satellite-based links with medium TRL should be targeted. Showcase a network of physically distant processing nodes (e.g. in the quantum memory). This should target at least 20 qubits per node and be programmable in platform independent software. Clear progress towards a robust supply chain for quantum communication is desired. Space-based QKD sub-systems for should target TRL 7.

Academic and industrial work promoting standardisation and certification should be addressed at every stage.

Quantum Computation

A quantum computer is a device that harnesses the laws of quantum mechanics to solve tasks in a more efficient way than classical computers. The objective on hardware research is to develop and demonstrate such devices. Further objectives include the development of quantum system software and dedicated algorithms to solve specific tasks, and the creation of interfaces between quantum computers, communication systems and classical computers. The construction of universal quantum computers with thousands of error corrected quantum bits would have a tremendous impact. It would allow us to solve problems that the most powerful supercomputers are not able to handle.

The basic building blocks of quantum computers have been prototyped and demonstrated with many different technologies, including trapped ions, superconducting devices, spins in semiconductors, neutral atoms, photons and NV-centres in diamonds. As these technology platforms have different strengths and weaknesses among the requirements for quantum computing, they merit, in part, a continuous discussion and re-evaluation within the Flagship.

The development of commercial products will start with small devices applied in different areas, including quantum sensing, quantum communications and approximate quantum computation in chemistry. Universal quantum computers will be widely applicable, including process optimisation, machine learning, business process optimisation, finance and inventory management and quantum many body systems as they appear in different fields of physics, chemistry and material science.

Socio-Economic Challenges

The ability to process data fast will be a key driver for the future economy, where even marginal technological differences lead to valuable competitive advantages. As progress of traditional computing technologies is coming to its physical limits in size, power density, and price, new paradigms are sought after. Quantum computing is a post-Moore computing paradigm with the potential to provide qualitative acceleration of selected computational tasks.

Europe has pioneered the key elements of quantum computing and its research groups are globally competitive. It needs to be a focus of the Flagship to transform this starting position into competitive systems and applications. This includes to play out and enhance specific European strengths such as institutional support and diversity with universities, RTOs and SMEs, but also large companies and the European research programs. The topics need to be combined with targeted training and funding for system integration as well as ensuring close collaboration between quantum hardware and software specialists. The high demands on system integration of universal quantum computers requires a whole new hardware ecosystem with opportunities for spin-offs in areas including optics, solid state physics, electronics and computer science. In this ecosystem, ignition funding for both, small- and large-scale undertakings is a pivotal instrument.

Quantum algorithms and application software research is needed to both, discover new quantum algorithms as well as linking quantum algorithms to use-cases. This level of research is suited to engage with the industry for supplying and exchanging use-cases and to support start-ups to emerge with manageable risk and investment. On the academic side, quantum software research is carried out at several very visible research centres in computer science and in physics. However, quantum computing research needs to be fostered as a pillar of computer science research within Digital Europe. This is an important step for the central challenge of training quantum-aware programmers and users.

Research and Innovation Challenges

One of the most challenging function of the Strategic Research Agenda is to monitor the technology developments and, if needed, to name new technologies with potential to grow faster than what exists. In the first stage, the Flagship selected two technologies, trapped ions and superconducting qubits, to implement computing devices and platforms. However, semiconductor-based qubit technology is currently under consideration as a third technology to implement devices. On the side of fabrication of hardware devices, the innovation on how to apply and use quantum computing devices needs to be fostered.

A general intention is to create a healthy industry which has three key components: hardware, software, and the users. On the software side, there are two aspects, on one hand is the need for the development of an entire software stack which allows the integration of quantum computing into an existing computing environment; and on the other hand, dedicated back-ends are required to correctly drive gates and access qubits. Ideally, the user software and its interfaces will be platform agnostic.

Some general quantum computing specific future directions of research include:

* Further development of all current technologies to understand their limitations and find ways around them.
* Optimisation of the performance of quantum error correcting codes, by both increasing the error threshold and decreasing the overhead of required qubits.
* Investigation of new ways of performing quantum computation, such as self-correcting codes (as they appear in topological systems).
* Development of new quantum algorithms and search for problems where quantum computers will provide an advantage.
* Development of quantum complexity theory and its application to many body physics.
* Building architectures and interfaces between quantum computers and communication systems.
* Development of quantum-proof cryptography to achieve forward-in-time security against possible future decryption (by quantum computers) of encrypted stored data.
* Across the board reduction of native errors in quantum hardware.
* Fast I/O of quantum computers, quantum memories and its system integration.
* Scaling up quantum computer sizes without sacrificing operation fidelity.
* Quantum compilation of algorithms with respect to hardware capabilities and limitations.
* Standardisation of programming interfaces in both quantum computer applications and firmware
* Validation of universal quantum annealing as a viable alternative to gate-based quantum computing.
* Development of automated calibration and tune-up protocols for the different systems components, including initialisation, manipulation (quantum gates) and readout.
* Development of characterisation, verification, validation and benchmarking tools for quantum computers.
* Development of quantum programming languages, compilers and middle-ware stack.
* Investigate and develop proof of principle applications to verify and demonstrate quantum advantage.

1. Technologies, Devices and Platforms

The Flagship currently maintains quantum computing platform projects applying three different device technologies: Trapped ions, superconducting qubits and semiconductor-based qubits. These three technologies satisfy the five required criteria for quantum computing defined by Di Vincenzo: 1. A scalable physical system with well characterised qubit; 2. The ability to initialise the state of the qubits to a simple fiducial state; 3. Long relevant decoherence times; 4. A "universal" set of quantum gates; 5. A qubit-specific measurement capability.

Further qubit and platform types including impurity spins in solids, neutral Rydberg atoms, topological qubits and photonic qubits need to be considered as future candidates for quantum computing and most require development at the level of Basic Science, which is discussed later in the paragraph dedicated to collaborations.

**Trapped Ions**

Trapped ion set-ups have been the first successful platform for the demonstration of quantum information processing (including Shor’s algorithm for factoring numbers and quantum chemistry), with long qubit coherence times and high fidelities demonstrated for state preparation, single-, two-and multi-qubit gates, and state detection. All building blocks for initialisation, manipulation and readout have been demonstrated at the fault-tolerant threshold. Nevertheless, challenges remain on the path towards a large-scale quantum processor based on trapped ions:

* The ratio of coherence time compared to two-qubit gate time needs to be increased, for instance by employing proposed schemes for ultrafast laser gates, ultra-fast quantum gates based on Rydberg excitations, switching to different ion species, or general improvements on laser and magnetic field control.
* Although impressive progress has been made, scaling the trap architecture has proven a difficult task. In recent years, elaborate trap layouts have been realised using microfabrication processes, and high-fidelity gate operations have been demonstrated on micro-fabricated traps. The electric-field noise near trap surfaces, which is an obstacle to the miniaturisation of complex ion trap structures, has been reduced by two orders of magnitude; however, further improvements may be necessary for high-fidelity operations in highly miniaturised traps.
* Microfabricated ion-traps may benefit from improvements through integration of optics and electronics into micro-fabricated ion traps. Further developments are necessary for large-scale devices.
* Several challenges concerning vacuum, magnetic field, etc. can be overcome with cryogenic setups. Development of small-scale cryostats, potentially as side projects from the solid-state community efforts, could be beneficial for the development of compact cryo-systems.
* Large-scale ion-trap quantum computing, including quantum error correction, will benefit from two-species control for sympathetic cooling (during the quantum computation as well as in the context of transport based quantum control) and quantum state readout (in particular in the context of quantum error correction).
* Ion-trap quantum computers can, already now, include an optical interface to map ion-information onto photonic information. Here, a minimal quantum computer network consisting of 3-4 ion-trap quantum computers would represent a major step forward towards large-scale quantum computation.
* Ion-trap quantum computers, similar to superconducting systems, realise quantum control and manipulation via the modulation of carrier frequencies (optical for ions, and microwave for superconducting systems). The modulation is generally realised using arbitrary waveform generators in the frequency domain of about 50-300 MHz. It is possible, and likely beneficial, to join efforts across the two architectures to jointly employ similar or identical electronics.
* On the long run, 2D ion-trap architectures need to be pursued to scale beyond 1000 qubits. Numerous approaches (such as junctions on ion-traps, chess-board like RF segments with individual control, or micro-fabricated Penning traps) are currently being tested, without a clear winning candidate yet.

**Superconducting Qubits**

Superconducting qubits are applied world-wide by many research groups and demonstrated at very different levels, from two qubit gates to integrated systems with 20 qubits and full software support. The technology is ready for small systems integration of quantum computing in quantum sensing or quantum communications applications. In the context of quantum computing in a Noisy Intermediate Scale Quantum (NISQ) regime, combined with an error mitigation scheme, chemical simulation has been demonstrated with results at very high precision.

* Continuous qubit coherence improvements are a core parameter for future performance enhancements of this technology.
* Higher gate fidelity by shorter gate times is an important technology related performance parameter.
* Superconducting qubits are manufactured, not natural, and are therefore sensitive to imperfections (limiting yield and reproducibility of device parameters). This requires optimisation of the production process in order to reduce imperfections and enhance reliability.
* The device architecture, especially the graph representing direct qubit-qubit connections, has a high relevance. Gates rely on the structure of the graph which need to be optimised.
* Scaling up vs scaling out: besides the challenges of creating and controlling a few hundred qubits, it is a challenge to connect superconducting systems coherently through a high-fidelity network. Such interconnects will require coherent high-fidelity repeaters and converters.
* Superconducting qubit circuits operate below 50 mK and therefore require dilution refrigeration technology. While being an established technology, this need poses an extra challenge for the engineering of a large-scale quantum computer beyond a few hundred qubits.

**Semiconductor based Qubits**

Semiconductor-based qubits make use of today’s electronics technology. Employing nanofabrication techniques, quantum dots have been defined in which individual electrons can be confined. Also isolated donors have been positioned in semiconductor substrates and used to trap individual electrons. In both cases, the spin of one or more electrons is considered the most promising qubit representation, since spin coherence is longer than the coherence of charge states or other degrees of freedom. These devices can be measured and controlled fully electrically, again much like transistors in today’s digital electronics. Looking ahead, we identify several challenges that need to be overcome in order to push electrically controlled electron spin qubits to the next level:

* Materials research on relevant systems.
* Poor qubit uniformity and background disorder currently must be compensated for by tedious tuning of gate voltages.
* Low-frequency charge noise has been considerably reduced over the past ten years, but still sometimes slows down experiments (as some retuning is needed when background charges move).
* An increased understanding of the microscopic origin of high-frequency charge noise, and a reduction of charge noise levels, is needed to improve the fidelity of gates based on spin exchange, capacitive coupling, and other gates sensitive to electric fields.
* Creating precisely positioned donor arrays remains a challenge.
* Whereas many theoretical ideas have been put forward, a coupling mechanism and/or geometry that is suitable for creating 2D arrays of spin qubits remains to be demonstrated.
* Efficient schemes need to be developed to wire up increasing numbers of qubits on a chip operating at cryogenic temperatures.
* Compact, low-cost electronics (possibly in part cryogenic electronics) needs to be developed for read-out and control of increasing numbers of qubits.

2. Software / Algorithms / Use Cases

Although the theoretical background and underpinning of QIP is sizeable, it is important that a greatly increased effort is started to put the computer science aspects of this endeavour on par with the experimental hardware projects. Europe has to maintain and expand its leading position in this growing field. The questions below just give a flavour of some of the numerous issues to be addressed. On the algorithmic and application side, the range of real problems for which quantum computing truly provides an advantage is, as it is in classical computing, a very challenging topic and the thriving force and motivation behind the software industry. On the architecture side, one has to find the fault-tolerant schemes best suited to each qubit platform in order to allow experimentalists to perform computing tasks as advanced as possible given existing imperfections and limited qubit platforms. This points on one hand to a closer synergy between theory and experiment that Europe could help to build a functional quantum computer, and on the other hand to support platform agnostic algorithm and software design.

**Quantum Error Correction & Fault-tolerant Computation**

Despite its amazing power, a quantum computer will be a rather fragile device, susceptible to disturbances and errors. Fortunately, methods have been developed to protect such a device against disturbances and imperfections, as long as these are small enough. These methods are constantly being improved and refined, but there is still a lot of work to be done until we can run a quantum computer reliably. Error correction is the first step toward fault-tolerant quantum computation. In order to achieve this new model of computation, new schemes need to be developed.

**Compilers & System Stack**

There is a big challenge on investigating and developing optimiser compilers for quantum computation. These compilers need to identify in a large code segment the piece of code addressing a suitable problem which can be efficiently translated to and solved by quantum computation. This is a hard requirement to integrate quantum computation in our common computing infrastructure. Further, quantum computing need to be transparently integrated in today’s middle-ware stack.

**Quantum Algorithms & Application Areas**

A constant challenge in this field is to find new examples of problems for which a quantum computer equipped with the right software and algorithms outperforms the best-known classical algorithms. The community has by now developed a good toolbox of quantum algorithmic techniques (very much akin to classical computing). One of the challenges is to exploit and apply these techniques to practical and industrial use-cases. It is also important to establish limitations both on classical computers as well as on quantum computers in order to assess when and for which computational and industrial problems quantum computers offer an advantage. Both the quantum algorithmic toolbox and these impossibility results (e.g. fine-grained complexity) are needed to develop optimal quantum solutions. Moreover, insights into the limitations of quantum computers can also be exploited in quantum-resistant classical and quantum cryptography.

Some application areas have been identified. For example, the simulation of quantum mechanical processes may become the first short-term application of quantum computers. Non-error corrected quantum computers may be able to perform such quantum mechanical simulations that are impossible on classical computers. They could be used for a variety of purposes, e.g., to obtain an accurate description of chemical compounds and reactions, to gain deeper understanding of chemical reactions, high temperature superconductivity, or to find out the reason why quarks are always confined. It is important to have a close cooperation with industry and the European large research facilities in order to assess their computational needs and co-develop quantum algorithms.

**Benchmarking Quantum Computers**

There exist several benchmarks which depend on the quantum technology pillar (sensors and clock, communication, simulation and computing) as well as the architecture. While there are architecture-independent metrics and benchmarks available, they will nevertheless remain to be different per pillar.

Within a pillar one could pursue a community driven approach similar to the established techniques for the Internet: Suggest benchmarks and metrics via ieft.org, in particular routines with a Request For Comment (RFC), such that suitable metrics and benchmarks can gradually evolve with the capabilities of the community. This very general approach is in particular compatible for quantum communication, quantum simulation and quantum computing - and can be adapted to be platform-independent. This concept can be applied to our Flagship project internally. However, it would be an attractive approach to internationalise this idea, fund an association and invite international research groups and industries to contribute.

For quantum computation it is important to go beyond the number of qubits. However,a quantum hardware and low-level quantum software agnostic method is required to avoid optimising devices onto the benchmarking method instead of focussing on the user applications. Like today’s HPC systems validation, we need a standardised suite of algorithmic benchmarks (e.g. number factored, molecule size) to take different resource demands into account. These benchmarks should allow one to address both, the current NISQ regime as well as the later fault tolerant quantum computing, with a resolution which allows characterisation on device, platform or full system level.

3. Supply Chain

Enabling technologies will be the “picks and shovels” (one of the most commercially successful economic branches during the gold rush) of quantum technologies. Leadership in quantum technologies hinges as much on these enabling technologies as it does on combining systems for entirely new applications. It is therefore of crucial importance to ensure access, within Europe, to the key enabling technologies and a suitable, reliable supply chain. This includes photonics (lasers, light-distribution, fibre-technology), electronics (in particular high-speed phase-coherent control of RF and microwave fields), high-capacity cryogenics, as well as micro- and nano-fabrication capabilities for several materials to realise semiconductor quantum dots, novel ion-traps, atom chips, as well as superconducting systems. This also includes quantum software development for both hardware as well as industrial use-cases. Creating spin-offs or engaging small companies can be complex. So, supporting these possibilities will help here. However, motivation for large companies to join the program relies on institutional actions and communication. For resources, we should join together everything that is available in Europe.

Roadmap

The roadmap has two stages. The first one describes milestones to be reached within the next three years. The second stage contains medium-term milestones which shall be reached in the timeframe of six to ten years.

**Vision in 3 Years**

In three years or less, several experiments should have reached “quantum advantage”, i.e., demonstrate a processor with a high number of qubits and an error rate low enough so it cannot be classically simulated any more. From there, the main challenge will be to solidly corroborate this regime and approach a first generation of applications while steadily improving the capabilities of the hardware.

With this, it is important that a supply chain is developed bottom up, from the current needs of projects in professionalisation of hardware and engineering, so it can meet software-driven top-down approaches halfway. This is in particular important for photonics, cryogenics, control, and manufacturing of qubit hardware. It needs to be noted that outside the academic world, software is already much stronger in Europe than hardware.

*Some specific challenges include:*

To move from lab to market: Fault tolerant routes demonstrated for making quantum processors with eventually more than 50 qubits Identify use-cases where quantum performs better than classical. Identify new use cases made possible by quantum. Identify new use cases for enabling technologies developed thanks to efforts in QT. Quantum algorithms demonstrated in NISQ regime with error mitigation. Also better exploitation of foundries, motivate hardware industry to contribute (control electronics, optical communications, RF communications), and motivate software industry (existing companies and start-ups) to contribute.

In terms of Research and Innovation challenges exist for: materials development, quantum device physics, qubit and gate control, photonics, RF-electronics, cryo and superconductor electronics, system engineering, and device packaging, quantum application theory, HW agnostic benchmarking NISQ based systems, and software architecture, compilers and libraries, integrated photonics, cryo- and superconductor electronics, as well as EDA and simulation tools.

Joint actions with other fields such as material science, theoretical physics, cryo-physics, electrical engineering, mathematics and computer science, are needed. Similarly, Standards bodies (EU, international) and Industry (foundries, design and simulation tool suppliers) are much needed.

**Vision in 6 to 10 Years**

Scalability is seen as a key for the medium-term. We need to be prepared for the systems point of view, including assembly and package technology, device and systems development, and integration. For this integration task the European-wide available facilities and a strong involvement of engineering capabilities are absolutely required. We also need to identify key components for large scale high-performance computers and make sure they are available in Europe.

The current approach is sufficient for small numbers of qubits, however, we need to focus on going to larger number of qubits, once the few-qubit milestones are met. We have identified applications for quantum computing based on a small number of qubits. However, universal error-corrected quantum computing and its applications require large numbers of qubits. Therefore, we need to motivate the industry to invest in development and manufacturing of quantum technology and the resulting ecosystem for hardware, software and applications.

*Some specific challenges include:*

To move from lab to market: Quantum processor fitted with quantum error correction or

robust qubits demonstrated, outperforming classical computing. Quantum algorithms demonstrating quantum speed-up and outperforming classical computers. Foundries able to manufacture required technology, including integrated photonics, cryo and superconducting electronics, as well as engagement with established instrument builders and software houses

In terms of Research and Innovation challenges exist for: materials, quantum device physics, qubit and gate control, quantum memories, photonics, RF-, cryo- and superconductor-electronics, system engineering and device packaging. HW agnostic benchmarking which also includes digital, error corrected, systems, optimizing compilers and libraries, as well as developing an integrated toolchain (design to processing) and primitives libraries for integrated optics, cryo and superconductor electronics.

Joint actions with other fields such as: Material science, Theoretical and cryo physics, electrical engineering, maths, computer science, and increasingly, scientists working in potential application fields and industry (small and large entities). Standards bodies (EU, international), industry (foundries, design and simulation tool suppliers) and EU infrastructure (labs) will be needed to maximise impact and success.

**Types of Projects and Instruments**

The Quantum Computation Pillar originally was organised with two-platform development projects on trapped ions and superconducting qubits. However, due to the technological development, a third platform on semiconductor technology has been added. The need to bridge from hardware platforms to the users a software project has been added. For future technology directions, close collaboration on Basic Science aspects is required to ensure long-term success. Furthermore, collaboration with the quantum communications and sensing pillars will create possibilities to demonstrate the application of small quantum computation devices.

**Collaborations within the Flagship**

A paramount task of the Flagship is research on alternative quantum computing technologies, such as impurity spins in solids, neutral Rydberg atoms, topological qubits, valley-qubits, photon qubits and molecular spin qubits. If breakthroughs happens in one of these technologies, an additional platform development effort may need to be initiated. Therefore, strong efforts in Basic Science are essential.

These research projects and novel approaches, applied to quantum computing, have an extended set of directions and requirements, which generally include:

* In systems with several interacting NV centres within a small volume the dephasing needs to be analysed in, and addressed with, optimal control theory to assess scalability.
* Nanoengineering of micro-cavities, high precision ion implantation and advanced crystal growth techniques need to be further developed but also have the potential to bring game-changing improvements to the impurity doped solids.
* Develop topological writing/reading combining optical and electrical techniques
* Research on semiconductors and magnetic materials.
* Develop laser technology: Lasers are promising and can be topologically manipulated to address a quantum device.
* Create 2D arrays of topological spins using optical matrix transfer to increase the integration.
* Dedicated compact, low-cost electronics.
* Implement probabilistic computing. This is an alternative data processing concept where information is transferred in the form of probabilities compatible with quantum computing architecture
* Develop the associated ultrafast laser technology - fibre laser are promising to address a quantum device at low-cost.
* High-quality photons require cryogenics, this demands further technological developments regarding packaging
* Research for reliable, reproducible fabrication of photonic cavity-emitter devices.
* The implementation of photonic quantum information processing units requires large-scale, high-efficiency PIC devices, fast optical modulation, and near-unity efficient photon detection.
* Scheme for short term quantum memories should be devised to go beyond the threshold of 100. Such memories can be developed with similar spin-photon interfaces as the one developed to generate the photonic cluster states.
* While some theoretical proposals have been proposed, a technology able to control, read-out and wire up large arrays of magnetic molecules remains to be demonstrated experimentally.
* Despite recent encouraging results, coherent coupling of individual molecules to single photons in on-chip superconducting resonators needs to be achieved.
* Coherence times in multi-qubit molecular structures need to be improved by two or three orders of magnitude
* Depositing individual molecules onto specific areas of a circuit still remains a challenge.
* Compact, low-cost electronics (possibly in part cryogenic electronics) needs to be developed for read-out and control of increasing numbers of qubits.

**International Collaborations**

Quantum technologies penetrate a wide range of applications and thus also rely on an exceedingly wide base of developers that can and should participate in the development of quantum technologies. Beyond the physicists that are currently strongly represented in the Flagship, it would be highly beneficial to create cross-connections towards mechatronics for the engineering of next-generation quantum simulators and quantum computers, electrical engineering for improved control of these novel systems, and computer science for the development of new algorithms and use-cases to be realised in both quantum simulators and quantum computers. There is also the question of developing collaborations across the Flagship for example communication and sensor/clock networks, but also in terms of metrology for the standardisation and certification of devices, systems and different functionalities. Joint conferences and establishing academic as well as industrial user associations are obvious solutions to improve exchange.

**Collaborations with other Fields**

Dedicated efforts to develop algorithm design and find use-cases. This may require us to divert resources towards that, as well as for basic science. Software is very important and control theory is critical for system operations. There exists open source software, however, this needs to be significantly improved for universal quantum computing. Collaborations needs to be coordinated with other projects and programmes on a Europe level, addressing Digital Europe, ESA, Euratom and large companies such as Airbus, Thales and ATOS. Similarly, for fast reliable electronics and quantum computation hardware, engineering and fabrication calls for the European infrastructure sites and foundries which have key priority for quantum computing.

Quantum Simulation

Quantum simulators are highly controllable quantum devices that allow one to obtain insights into properties of complex quantum systems or solve specific computational problems inaccessible to classical computers. The basic ideas go back to work by Richard Feynman, who noticed that precisely controlled quantum systems could serve as simulators even in situations intractable for classical devices. It was noted early on that a universal quantum computer could keep track of the dynamics of locally interacting Hamiltonian systems, a task that requires exponential resources on classical computers. Generally speaking, quantum simulators allow one to predict static and dynamical properties of complex quantum systems with very high levels of accuracy.

The notion of *tuneable* or *controlled* quantum systems is at the heart of a functioning simulation platform, rendering efforts towards an ever increasing level of control a central focus of current research activities. With the recent technological advances, reliable large-size systems can be realised, e.g., systems of ultracold atoms in optical lattices with ten thousand or more constituents interacting with each other, arrays of Rydberg-excited atoms in optical tweezers, or single photons propagating in arrays of waveguides or resonators. In this way, properties of quantum mechanical ground states can be characterised, or the dynamics of interacting systems out of equilibrium monitored and activated, in a way that is beyond the reach of known classical algorithms. General quantum systems can no longer be classically kept track of for moderate system sizes of about 40 constituents, a state of affairs that places, in particular, two-dimensional structures outside the realm of classical simulation. In this sense, existing quantum simulators are already comparably well developed. Present-day quantum simulators based on existing technology, even though still basic, already promise interesting applications within the scientific community, with significant near-term potential, possibly even in the industrial context.

The Quantum Flagship provides the potential for developing quantum simulators into highly capable quantum devices, as well as their scientific and commercial potential. An important target is the achievement of higher levels of control and higher state preparation fidelities to establish new applications and directions for further development. A key challenge is to achieve large and programmable quantum simulators at the lowest entropies, allowing to approximate solutions to optimisation problems, or to address problems in quantum chemistry, nuclear physics, high-energy physics, or materials science. In contrast to full fault tolerant quantum computers, quantum simulators are devices that are anticipated to operate largely without the necessity of quantum error correction.

Quantum simulators are quantum devices that allow one to simulate intricate systems from condensed matter and high energy physics, materials science and quantum chemistry. Going beyond natural systems, Quantum Simulator can also provide novel synthetic quantum materials with no equivalent in nature and completely new physical properties. One can distinguish between static and dynamical quantum simulators. The former assess static properties, i.e. ground state or thermal properties, such as ground state properties of the fermionic Hubbard model that promises insights into the functioning of high-temperature superconductivity. The latter explore dynamical properties outside the reach of classical computers, such as out of equilibrium properties of many-body localised systems that violate expectations of quantum statistical physics. Different approaches to quantum simulation can be classified in the following fashion:

* *Digital quantum simulators* approximate local quantum dynamics in a stroboscopic fashion, involving a variant of the Trotter formula. Digital quantum simulators are intrinsically programmable due to the approximation of the target dynamics starting from a few basic building blocks.
* *Analog quantum simulators* emulate other quantum systems under precisely controlled thermodynamic and interaction conditions. In particular, these simulators go beyond a computational paradigm based on qubit systems, 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* such as programmable quantum simulators, annealers, variational optimisers, or variants of quantum approximate optimisers and other noisy intermediate-scale quantum (NISQ) devices aim at providing approximate solutions to optimisation problems. Here, often both a classical and a quantum component comes into play in instances of hybrid schemes operating without quantum error correction. Here, the potential for technological application is high, but a significant amount of ground work is still required to understand the potential of heuristic quantum devices.

Socio-Economic Challenges

The efforts in quantum simulation are expected to have a key impact on several socio-economic challenges.

* Europe has an extremely strong chemical and pharmaceutical industry. This industrial base is extremely important for many key technological challenges of the future, like electrical mobility. While battery-cell production is dominated by Asian companies, Europe still has strong battery material suppliers. The synergy with efforts in the field of quantum simulation are obvious. Industries in Europe can greatly benefit from improved possibilities to simulate materials. At the same time connecting the quantum simulation pillar to industrial customers can greatly benefit the quantum technology efforts.
* The efforts on quantum simulation contribute to making Europe an attractive region for highly innovative research and business, accelerating their development and take-up by the market. This applies in particular to mid-term devices that promise to offer solutions to problems of end-users in optimisation, routing and scheduling, but potentially also to cloud services. The potential of applications is expected to contribute to a competitive European industry, both in hardware and software, and to position Europe as a leader in those endeavours.
* Learning to control large-scale quantum systems at a quantitatively new level requires creative ideas. On the one hand, Quantum Simulators can account for complex interparticle interactions, as the long-range and anisotropic interactions relevant e.g. for quantum magnetism or to mimic biological-relevant cases. On the other, they allow for tests of novel situations by engineering correlations and entanglement among particles. Moreover, Quantum Simulators are not limited by the qubit paradigm, which opens up the search space for a scalable and programmable approach to this outstanding problem. This complementary approach to controlled quantum dynamics has the potential to lead to important new discoveries, which provide an alternative viewpoint and better understanding of outstanding challenges in material science and quantum chemistry.
* These efforts are expected to consolidate European scientific leadership in a field of research and development where it has already achieved a world leading position. This leadership is also expected to have a decisive, positive impact on training activities. It will bring the concepts of quantum mechanics closer to the centre of society, which by itself has the potential to spark new ideas and approaches to problem solving.

Challenges are arising from establishing a closer contact with the end-users, finding more convincing applications of near-term devices with no quantum error correction, especially also of itinerant, non-qubit based, simulators. It has to be established in what precise way quantum simulators featuring no quantum error correction can have a quantum advantage.

Research and Innovation Challenges

Europe is particularly well placed internationally to take a leading role in the development of quantum simulators, given the impact it has had on the field so far. Quantum simulators are expected to provide unprecedented insights into complex quantum systems and materials. At the same time, programmable quantum simulators and other NISQ devices promise important applications for end-users. For this to be possible, significant research and development are still required, in a highly competitive environment. To maintain the leading position Europe has established, and in order to bring efforts to a new level, there is a need to ensure a sustainable supply chain of both technologies and human resources to contribute to building a European quantum industry. In the following we will summarise some of the main challenges that need to be addressed.

1. Platforms and implementations

Quantum simulators naturally cover a large variety of platforms. There are not only platforms to implement digital quantum simulation and heuristic quantum devices, but also different platforms for realising analogue quantum simulation. As the latter aim to directly mimic the target system, the breadth of platforms is large.

**Ultra-cold atomic and molecular quantum gases** constitute one of the most prominent and promising platforms for quantum simulators. There are a number of architectures being developed with increasing ability to tackle complex problems. These include systems of ultracold atoms in optical lattices with short- and long-range interactions, and continuous systems confined in atom chips. Recent key achievements have been the realisation of the superfluid-to-Mott-insulator transition, entanglement propagation in spin systems of dipolar atoms, and the first quantum simulations of the Fermi-Hubbard model. Besides dipolar atoms, strong coherent interactions spreading over long distances, have been recently created in reconfigurable arrays of individually trapped cold atoms, excited to Rydberg states. This platform allows for programmable analogue and digital quantum simulators. Moreover, their fast data rate renders them also prime candidates for the implementation of heuristic quantum approaches. Future work will aim at higher levels of control, larger systems, and better read-out techniques, beyond what is possible with present quantum gas microscopes. Another outstanding challenge is the need for lower entropy, i.e. higher fidelity, initial state generation.

**Trapped ions** are a second key platform for realising state-of-the-art quantum simulators. The extraordinary level of control of motional and internal quantum states enables the realisation of prototypes of both digital and analogue quantum simulators, featuring programmable short-range and long-range interactions. Rydberg states can also be realised in systems of trapped ions. A key challenge is to scale up the system size - possibly using segmented traps - and to improve coherence times. Recent efforts include verifiable variational quantum simulations, opening up perspectives of achieving near-term programmable quantum devices.

**Superconducting qubits** offer a wide range of applications in quantum simulations. It has become clear that superconducting devices allow for quantum simulations under highly controlled conditions, specifically when realising qubits in a one dimensional chain with adjustable coupling between every pair of qubits of a GMON architecture. For this type of quantum simulation platform, system sizes are comparably small, but at the same time offering large degrees of control.

**Photonic simulators** make use of single photons in complex networks to generate complex many body entangled states. These single photons are generated by single photon sources or emerge from strong non-linearities in lattices of resonators. These simulators are scalable and integrated platforms, some compatible with the most advanced opto-electronics and nanotechnologies. Solid state as well as atomic single photon sources and non-linear resonators required for such applications are rapidly reaching maturity.

**Further quantum simulation architectures.** There are a number of other prominent quantum simulation platforms being developed and refined, including architectures of polariton condensates in semiconductor nanostructures, circuit-based cavity quantum electrodynamics, arrays of quantum dots, that already have commercial applications in quantum annealing, and photonic platforms. Other prominent architectures include spins in solids such as ensembles of colour centres in diamond or the use of colour centres to control other electron or nuclear spin ensembles for the purposes of quantum simulation.

**Figures of merit and benchmarking.** There are several figures of merit for the success of quantum simulations depending on the specific path used. For digital quantum simulators and variational approaches, figures of merit of average gate fidelity of individual quantum gates apply to quantum simulation as well. For circuits as a whole, the quantum volume gives rise to a good heuristic figure of merit, as a meaningful figure of merit in its combination of connectivity, number of qubits, average gate fidelity and number of gates. For analogue quantum simulators, different figures of merit can be relevant depending on whether the application is more simulation- or solving-oriented. These include e.g. coherence, speed of entanglement propagation, and local or global entropy.

2. Exploitation and Use-Cases

Concerning exploitation and use cases, three types of applications are in the focus of interest. To start with, analogue quantum simulators offer unprecedented insights into strongly correlated quantum systems within the scientific community. Then, quantum simulators can be used to simulate fermionic systems like molecules or condensed matter systems. The relevant algorithms are often called 'hybrid' algorithms because a close interaction between quantum and classical computers is necessary, in settings in which the quantum system is used as a subroutine in an otherwise classical algorithm. Finally, on the side of a quantum computer without full quantum error correction, the focus is on algorithms that can be implemented in the medium-term and that require only a very small number of operations. This is necessary because quantum computers are currently relatively error-prone and each operation is performed error-free only with a certain probability (fidelity). Applications seem possible with gate fidelities of 99.5% -99.95%. This is often described as NISQ (near-term intermediate-scale quantum) applications.

The integration with classical, numerical methods allows the optimal preparation of the material problem: the separation into an efficiently classically treatable part and one that isolates the quantum mechanical complexity (in the form of strong electronic correlations). Methods of this kind are also available in limited form in existing quantum chemistry. For example, the CASSCF (Complete Active Space Self Consistent Field) method is well known. The defined active space is severely limited on classical computers. On quantum computers without quantum error corrections that can be seen as instances of quantum simulators, however, significantly larger spaces can be selected. This promises substantial improvements in the accuracy of material simulations. Current methods allow at most for qualitative study which substantially limits the application of simulation methods in material development. Higher accuracy that allows for quantitative predictions could have a vast impact in the development of new functional materials and drugs.

Programmable near-term quantum simulators and near-term devices without quantum error correction promise applications in solving or approximating solutions to optimisation problems and may be helpful in realising instances of quantum machine learning. Specifically, quantum-classical hybrids have emerged as promising candidates in realising quantum approximate optimisation algorithms. Such hybrid and other variational approaches are also prominent in discussions on realizing primitives of quantum-assisted machine learning, including quantum kernel methods.

Coherent quantum annealers suggest approximate solutions to optimisation problems that may indeed computationally outperform classical computers. This includes applications for traffic flow optimisation, aspects of computational fluid mechanics or the approximation of solutions to routing and scheduling problems.

3. Supply Chain

The key to success in quantum simulation is related to enabling technologies. Indeed, a European leadership in quantum simulation can be maintained if such enabling technologies can be put into good use in new applications of quantum technologies. Given that for quantum simulation, various architectures are being considered, the relevant supply chains largely depend on the platform chosen. The supply chains include the development of novel photonic components, of innovative fast and efficient detectors, of techniques for the manipulation of ultracold atoms and ions, of electronics, high-capacity cryogenics, and optimal control techniques. It also includes capabilities for fabrication of the most advanced materials (i.e., quantum dots, colour centres) when it comes to solid-state based platforms of quantum simulators. On the side of software and compiler development, new ideas of variational eigen-solvers and of quantum-classical hybrids are part of the supply chain, in order to fully develop the potential of quantum simulators without quantum error correction in its use in mid-term practical applications.

Roadmap

**Vision for 3 years:** The perspectives for quantum simulation centre around learning properties of physical systems and making use of programmable quantum simulators to solve near-term problems of end-users. Applications can be identified in solving practical routing and scheduling problems, and in offering cloud services in the quantum simulation of strongly correlated quantum systems and materials.

Achieving a “quantum advantage” is seen as an important milestone, but not as an application as such. Notions of quantum machine learning are widely regarded as highly exciting and fit quantum simulation goals. The interest of end-users into such applications is very large. Here, near-term programmable devices and quantum simulators promise to offer a speedup in instances of machine learning problems, including quantum kernels to quantum classification schemes. Overall, there is a need to improve levels of control and scalability, achieve a further entropy reduction in various platforms, explore potential of programmability of quantum simulators. Develop quantum-classical hybrid architectures. Bring various platforms of quantum simulators to a level so that they can be accurately compared on the same test problems.

In order to develop a vision for the coming three years, it is important to oversee the precise needs of industrial partners and end-users. Stakeholders should contribute to identify the problems that are interesting for them to justify better the scope and key goals of quantum simulators. For this, close interaction with industrial partners is key: Efforts should be close to the needs of companies with quantum simulation applications. All stakeholders should be brought together to Identify further applications in the study of complex quantum systems and end-user applications. Efforts to expand and strengthen the supply chain, the development of key enabling technologies and improving notions of control of quantum simulators as well as entropy reduction and interaction engineering should be supported throughout.

Finally, it is widely acknowledged that notions of certification are again key to a good functioning of quantum simulators. As in all other applications of quantum technologies, certification, benchmarking and tomographic recovery seem highly important.

**Vision for 6-10 years:** The most important element of a sustainable vision is for the field of quantum simulation to establish a close link to end-users and to develop more practical applications. Quantum simulators are very well-placed to achieve this aim, in a sometimes underappreciated fashion. Fault-tolerant quantum computers offer a wide range of applications, but they will most likely not be available within this time frame. Programmable quantum simulators and other near-term devices without error correction, in contrast, are expected to offer near-term practical solutions. This requires significant research and development, both on the hardware side to achieve quantum simulators offering a higher degree of control and programmability. At the same time, it is not yet fully clear what the potential is for near-term applications, e.g., in quantum machine learning, and in what precise sense speedups can be expected, Identification of the potential of quantum devices without quantum error correction.

From the perspective of learning physical properties, applications in quantum chemistry are among the most exciting ones. The demonstration of quantum simulation platforms unambiguously outperforming classical computers, solving problems in complex quantum systems and materials science with quantum simulators should be supported. It is also generally acknowledged that a close and sustained dialogue with companies is required to generate and maintain an interest in investing in quantum simulation. There is a need to expand the patent portfolio associated with quantum simulation.

The efforts on hardware development are accompanied by quantum software development with notions of computer science are expected to play a greater role also in research and innovation. Indeed, close interactions with material science and the study of complex quantum systems on the one hand and of algorithmic development in optimisation problems on the other hand are anticipated. A number of quantum software companies have emerged within Europe; it is an important incentive of realising quantum algorithms and algorithmic components on near-term programmable quantum devices that can be seen as being quantum simulators. It is important to build a bridge between the industry and research on quantum simulation and computing. It is key to translate the problems of industry in the language of our computing and simulation paradigms. In this context, it is emphasised how important it is to create a roadmap written for usual industries. This seems even more important in the light of the observation that Europe is at the forefront in quantum simulation.

Quantum Sensing & Metrology

The impact of quantum metrology and sensing technologies is broad and considerable, with many applications in every-day life. Technologies range from positioning systems, clocks, gravitational, electrical and magnetic field, force, pressure, and temperature sensors, quantum electrical measurement standards, NMR, ultra-high-precision spectroscopy and microscopy, to optical resolution beyond the wavelength limit. Sensing and metrology will be enhanced in many ways by quantum technologies: better accuracy and stability together with longer term integration as well as novel traceability chains to the revised International System of Units (SI), will yield enhanced sensitivity when exploiting quantum-enhanced precision well beyond the classical and standard quantum limits (SQL).

Important use-cases include medicine, physics, chemistry, biology, geophysics, climate-science, environmental sciences, defence or data storage and processing. Novel imaging sensors will have a large impact in the medical sector, e.g. magnetometry to image brain activity. Many applied and fundamental experiments in physics will profit enormously from the increased use of quantum sensing and metrology. Geophysics and climate change will profit for example from improved gravitational sensors for the detection of oil, gas, minerals as well as the monitoring of sea levels and ground water on a global scale (ESA- GOCE follow-up). Defence and autonomous navigation will profit from long-term stable rotation and acceleration sensors based on quantum technologies.

The central concept of a sensor is that a probe interacts with a system that carries the property of interest, and changes the state of the probe. Measurements of the probe may reveal the parameters of this property. A unique feature of quantum sensors is that the probe can engineer the state of the probed object, thus becoming entangled with it. Quantum-enhanced sensors either take advantage of the absence of classical noise processes, use a quantum algorithm for extracting the relevant information, or even employ probes that are prepared in a particular (many-body) non-classical state. Control over all relevant degrees of freedom and long coherence times enable 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 techniques are necessary. It should be stressed that the character of coherence and entanglement as resources are the subject of the field of resource theories which examines the laws of quantification, manipulation and interconversion of such resources in order to establish optimal operating conditions and optimal use of resources for quantum sensors. Besides performance beyond the standard quantum limit, quantum sensors offer advantages in terms of their size, operating environment, being drift and calibration free, and potentially simpler traceability to the SI unit system compared to classical measurement devices.

Because of the wide range of prospective applications and their specificity, a broad range of physical platforms needs to be considered, including (but not limited to) trapped ions, ultra-cold atoms, room-temperature atomic vapours, nano- and micro-mechanical oscillators, superconducting and semiconducting nanocircuits, artificial systems such as quantum dots and spin defects in solid-state, as well as all-optical set-ups involving non-classical states of light. In a first step, quantum sensors will exploit state superposition in a single quantum object on a variety of different platforms leading to new functionalities, improved performances or easier conditions of use. These applications have perspectives for reaching the level of a demonstrator in the near-term, while some are already at the production stage.

In a second step, these initial devices and systems will look to improve their size, cost, robustness and reproducibility. It will also see quantum sensors that exploit the full properties of “exotic” quantum states to achieve performances surpassing those of classical counterparts. Initially, high-performance sensors for specific applications are expected to drive development, and in the future, these technologies are expected to have a relevant position in the mass market, but this position will be gained only once proper quality assurance and standardisation has been developed.

Socio-Economic Challenges

Over the past decades sensors have become a key element in everything from cars to washing machines to smartphones. Allied Market Research estimates the market for sensors was worth 140 Billion USD in 2017 with a projected annual growth rate approaching 10% for the next 5 years. The reality is that without sensors a large part of the automotive and mobile economy would not have been able to grow. A number of European actors (NXP, Infineon, Bosch, STMicroelectronics to name a few) are leading the market making Europe a competitive actor in the field.

By addressing the demand for high performance sensor and metrology tools for applications in healthcare, security, electronics industry, and research, quantum based solution promise to further grow this market.

In this context, Quantum Sensing and Metrology will address a number of socio-economic challenges, summarised below

**Market identification**

* Identification of successive niche applications to progressively drive the European production capabilities to scale.
* Definition of standards and certification to allow large scale deployment across different segments.

These are fundamental steps to kick-start a competitive European industry in quantum technologies and to position Europe as a leader in the future global industrial landscape. Europe has the potentiality to become an attractive region for innovative research, business and investments in QT, but to achieve this it is necessary to accelerate the development and take-up by the market, which would be further enhanced through dedicated standardisation and certification efforts.

**Employment and education**

* Continuous training of highly qualified engineers, technicians, but also business developers and sales force with exposure to quantum concepts.
* Increase the offer for competitive job profiles for Europe’s brains (cutting edge technology, dynamic ecosystem and financial incentives)

**Development of healthy and competitive ecosystem**

* Supply chain: by bringing together key actors in Europe and supporting actions to fill in the gaps, Quantum Sensing and Metrology can strengthen Europe’s competitivity and leading role in the field, as well as European sovereignty.
* Ecosystem: it is crucial that Quantum Sensing and Metrology can support start-ups and SMEs as well as contribute to increasing awareness of quantum based solutions within larger companies to nurture the ecosystem and maximise success through exchange of ideas or partnerships.

**Dissemination**

Quantum Sensing and Metrology will contribute to making available to society new products with direct impact on healthcare, life quality, security, and the development of an energy efficient economy, as well as supporting certification, standardisation and quality assurance.

Specifically, between the quantum flagship pillars it is expected that quantum sensing and metrology will provide a large variety of technologies and solutions. We can identify two main product categories: small and inexpensive quantum sensors for mass-market applications and high-performance, high-cost quantum sensors for selected, niche, applications and a smaller market. In this second category we can also consider calibration services devoted to certification of these novel quantum devices.

**Research and innovation**

* Consolidation and expansion of European scientific leadership and excellence in research.

Indeed, it is fundamental that Europe consolidates and expands its scientific leadership and excellence in quantum research, including training the relevant skills, which are inherently interdisciplinary.

Research and Innovation Challenges

Quantum sensors are presenting both, new technologies to address current sensing tasks more effectively, and going beyond the boundaries of what can be detected with present day technologies. Therefore, any quantum sensor should outperform existing sensors in at least one of the following criteria: size, operating environment, sensitivity, specificity, statistical or systematic uncertainty, calibration intervals, lifetime, traceability. Benchmarking against existing reference systems for verification is necessary.

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
* Identify correlated quantum states that outperform uncorrelated systems in a noisy environment and methods to prepare them reliably
* Develop quantum algorithms to enhance sensor performance (sensitivity and spectral resolution)
* Tap into expertise and join forces with other fields, such as the signal processing community to implement the best control protocols, statistical techniques and learning algorithms
* An interesting avenue to pursue is that of technology development for improved and new space-based time and frequency transfer (TFT) techniques capable of going beyond current ESA missions (such as ACES) and achieve better performances. This might be done through TFT infrastructures based on a few geostationary satellites endowed with dedicated equipment and laser terminals. A complementary approach consists of an ensemble of low-orbit mini-satellites with appropriate links.
* Combine physics and signal processing methods such as Bayesian inference or machine learning techniques to further advance the limits of sensors sensitivity and resolution

Applications and commercialisation require the development of miniaturised, integrated, cost efficient and user-operable quantum sensors. To achieve this, the following technological challenges need to be addressed, wherever possible jointly with the other pillars:

* Fabrication, material and packaging solutions
* Improved access to facilities, e.g. Integrated photonics and electronics
* Electronic and optics integration into sensor platforms
* Miniaturised laser and vacuum systems
* Exploitation of micro-electro-mechanical systems (MEMS) and micro-machining
* Definition of standard interfaces between components
* A common open source control software platform

The challenges facing Quantum Sensing and Metrology can be addressed in two phases. Near-term applications, where first principle devices and systems are developed in parallel to advancing longer term concepts. In a second phase, these first devices should go beyond proof of principle towards higher TRLs ready for market uptake. In parallel here, the emerging approaches should be matured and work towards proof-of-principle demonstrations. In the following we elaborate on these with respect to the near- and longer-term application potential.

1. Near-term applications

First application targets here are for enhanced measurement and metrology of current, resistance, voltage and magnetic fields, as well as prototypes of integrated compact field sensors for e.g. chemical and materials analysis, medical diagnostics, labelling, trace element detection, enhanced imaging and spectroscopy with very low light intensity. Other approaches include sensors of gravity rotation, gradient and acceleration, e.g. for civil engineering, Earth observation and navigation. Optical clocks for timing and network synchronisation provide critical enhancements for infrastructure as well as having synergies with quantum communication networks. Similarly, radio-frequency, microwave and optical signal processing for e.g. management of the frequency spectrum in communication applications. Improved optical sensing and imaging using non-classical or entangled light, e.g. super resolution microscopy, or entangled two photon spectroscopy. Single photon detectors and arrays, or cameras, for optical spectroscopy, imaging and LIDAR. The application of optical clocks and electrical standards should target medium TRL up to technical validation in relevant environments, all other applications should demonstrate at least low TRL up to experimental proof of concept.

2. Longer term applications

As control and understanding of Quantum Sensing and Metrology technologies improve we will look to more advanced application solutions. Inertial sensors and clocks (microwave and optical) will be available as compact, autonomous, field-usable systems (medium TRL). Sensor networks for earth monitoring and tests of fundamental physics will be available (low to medium TRL). Optical interferometers, e.g. for gravitational wave detection, will operate with optimised squeezed states (low TRL, experimental proof-of-concept). Compact, integrated solid-state sensors will address applications such as healthcare or indoor navigation (low to medium TRL). Spin-based sensors and entanglement-based sensors will address e.g. life-science, including Nuclear Magnetic Resonance (NMR) down to single molecule, entangled Two Photon Spectroscopy of atomic and molecular systems, Electron Paramagnetic Resonance, hyper-polarised NMR and Magnetic Resonance, Imaging (low TRL). Optomechanical sensors will allow for developing force sensing, inertial positioning devices, microwave-to-optical converters (low TRL). Sensors based on electrons and flux quanta in solid state devices will allow shot-noise-free ultra-sensitive electrical measurements and hybrid integration of different quantum devices (low to medium TRL).

Commercial sensors and large-scale sensor networks, including the required infrastructure such as a European frequency transfer network, (up to demonstration in operational environments, high TRL) will provide earth monitoring beyond the capabilities of classical systems and improved bounds on physics beyond the Standard Model. Solid-state and atomic sensors will allow development of commercial biosensors and universal electrical quantum standards (up to high TRL). Sensors employing entanglement will outperform the best devices based on uncorrelated quantum systems (medium TRL).

3. Supply Chain

Enabling technologies will be one of the first markets of quantum technologies in the foreseeable future. Leadership in quantum technologies hinges as much on enabling technologies as it does on combining systems for entirely new applications. It is therefore of crucial importance to ensure access, within Europe, to the key enabling technologies and a suitable, reliable supply chain. This includes photonics (high-stability lasers, light-distribution and -control, fibre-technology, chip-scale optical frequency combs), electronics (in particular high-speed phase-coherent control of RF and microwave fields), single photon microwave to optical frequency conversion, cryogenics, as well as micro- and nano-fabrication capabilities for diverse materials including photonic and electronic integration, e.g. to realise novel ion-traps, atom chips, opto-mechanical oscillators, as well as tailored colour centres and single crystal materials with almost no residual impurities over large volumes (mm3).

This also includes the development of quantum-aware-sensor-specific software and hardware as well as industrial use-cases for quantum sensors. Since the initial markets are expected to be small, it is paramount to support small companies and the creation of spin-offs, as well as industrial use-cases for quantum sensors. For resources, we should join together everything that is available in Europe, in particular taking advantage of existing foundries and large-scale infrastructure, such as the Laser-Lab Europe and other large-scale national and international research initiatives including COST actions or EURAMET.

Some of the required resources include: robust and low-cost stable lasers for atomic, atom-like and opto-mechanical systems; a broadening of vision for materials generally related to high-purity and high-precision, e.g. SiC and other dopants or colour centres in diamond as well as other crystals and wide-bandgap materials, isotopic material engineering, single ion and deterministic implantation and in general a need for ultra-precision engineering and manufacturing across all platforms; fabrication of special purpose and tailored systems, all from e.g. small scale vacuum systems with integrated optical and e.-m. traps for atoms and ions to preparation of tailored nanoparticles for plasmonics. We also need a better synergy between technology platforms and optimise the coordination with big RTO platforms complying to long-term roadmaps and smaller academic platforms having more flexibility.

The supply chain may also include things like standardisation and also theory aspects like the development of control methods that achieve enhanced robustness and sensitivity at the same time, optimal experiment design as well as signal processing methods (post-processing) for optimal extraction of information from measured time series.

Roadmap

**3 year vision:** The objectives for quantum sensing and metrology include quantum sensors, imaging systems and quantum standards demonstrated in a laboratory environment outperforming classical or current state-of-the-art counterparts in one of the following criteria: size, operating environment, sensitivity, specificity, statistical or systematic uncertainty, calibration intervals, lifetime, traceability. Some specific targets include:

* Prototypes of transportable optical clocks aiming at 10-18 uncertainty, achievable in several hours of averaging time for height measurements and height system stabilisation in relativistic geodesy, as well as references for VLBI stations and GNSS timing facilities
* Optical clocks with high performance time transfer links
* Transportable atomic gravimeters outperforming classical systems by a factor of 5 in terms of statistical and systematic uncertainty for geo-prospecting
* Portable prototypes for magnetic detection of heart diseases, including foetal heart and brain signals
* Electric, magnetic, temperature and pressure sensors based on artificial atoms (e.g. colour centres, quantum dots, ...) or opto-mechanical and -electrical systems
* Demonstrate the practical usefulness of engineered quantum states, e.g. in quantum metrology
* Small scale vacuum systems often with integrated optical and e.-m. traps for atoms and ions.
* Nanofabrication, functionalisation and chemical modification of surfaces, e.g. for biosensing
* Synthesis of ultra-pure materials (diamond, SiC), doped nanoparticles colour centres, isotopic engineering of materials, including enrichment of diamond, single ion implantation technology
* Table-top prototypes for improving sensitivity of gravitational wave detectors beyond standard quantum limit
* Prototypes for detection of acceleration with nanomechanical oscillators
* Demonstrate quantum advantage of non-classical states of light for spectroscopy and imaging in chemistry and biology, or in-vivo, for low-flux regime applications
* Prototypes for room temperature nuclear spin polarisation for MRI applications
* Table-top prototypes of quantum-enhanced super-resolved and/or sub-shot noise microscopy
* Table-top prototypes of quantum LIDAR and RADAR
* Prototypes of compact quantum electrical standards with enlarged application ranges
* Demonstrations of magnetometry, e.g. to image brain activity.
* Miniaturised and cost-effective devices: compact diode lasers, microwave drivers, modulators and frequency convertors

**6-10 year vision:** The distinction between scientific and industrial challenges is important here as scientific goals in the 3-year vision may then be repeated as an industrial goal in the longer-term vision. Some specific targets include:

* Commercial magnetometers for improved MRI imaging, diagnostics of foetal heart disorders
* Deployment of quantum enhancing devices in large scale gravitational wave detection facilities and or quantum-based detectors.
* Space-ready optical clocks with 10-17 systematic uncertainty, achievable in few hours of averaging time and optical space-space as well as ground-space comparisons for future GNSS systems
* Commercial atomic gravimeters outperforming classical systems by an order of magnitude for geo-prospecting and earth monitoring
* Miniaturised atom-based magnetic & electric field sensors for magnetic imaging of materials and life sciences
* Quantum sensors for fundamental physics including gravitational waves, dark energy/matter, fundamental constants and spacetime parameters
* Sensing conformation changes of single molecules under physiological conditions
* Integrated lab-on-a-chip quantum sensors to facilitate commercialisation
* Nanoscale temperature sensors
* Commercial quantum-enhanced super-resolved and/or sub-shot noise microscopes
* Prototypes of quantum LIDAR and RADAR
* Integration of quantum electrical standards for self-calibration in instrumentation providing highly-accurate measurements
* Demonstration of Atom Trap Trace Analysis detecting rare radioisotopes for age dating in earth and environmental science

Scientific and Technological Resources

The long-term viability of a European quantum technologies industry requires a well-supported and dynamic effort in developing Scientific and Technological Resources (STR) through:

* Basic science for novel concepts and technologies,
* Cross-cutting activities - theory, software, engineering and control - for coherent approaches exploiting synergies and common needs across the flagship and all quantum activities.

Key resources exist and need to find a place in each of the four application domains. Anchoring resources within an applications area sends a clear message of how it feeds into future applications. But there are also many activities that actually will not crosscut, but have a place of their own. Similarly, there are basic science elements in many, if not all, of the selected Flagship projects, but obviously many things that may not fit there or require further exploration. Being able to support activities in these STR like fabrication, components & systems, as well as verification techniques, are also essential. All of these potential contributions are important and needed for a healthy long-term vision for the field.

STR provides maximum flexibility for the attribution of scientific and technological resources. On the scientific side, they may be used as an “entrance door” for new ideas or themes. On the technology side, they may help in sharing resources e.g. in nanofabrication facilities.

Scientific Resources

**Basic Science** is research that has the goal to understand and explore the science underlying all quantum technologies, both theoretically and experimentally. While remaining exploratory, basic science topics should aim to explore new quantum effects and gain new understanding that don’t fit in the pillar activities but which may contribute to new quantum technologies and applications in the long term. On the one hand, this includes scientific activities that are transversal and of relevance for several pillars. On the other hand, it also covers scientific directions that are in a very preliminary stage to be included in an existing pillar, but that can eventually make it in future stages.

For the success of the four application domains, the development of new scientific tools and concepts must be kept active and running. In fact, while some quantum technologies have reached a significant level of maturity and are ready for the transition to industry applications, 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 of the flagship. This will require the combined competencies of quantum and classical arenas to develop the tools, components, materials, processes that will enable the mission-driven objectives to be realised. This process is expected to work both ways: new science provides new ideas for quantum technologies, but also developing quantum technologies stimulates new questions to be answered by new science as well as experimental guidance for new theoretical developments.

This effort will be organised along a transverse domain of Basic Science, which will be broad and ambitious in its spirit and its goals. As a consequence, it would be impossible to give a prescriptive and exhaustive list of topics. Rather, this domain should be left open to any topic of basic quantum science.

The following are a few examples of research directions and goals among those that can be addressed.

**Quantum information theory.** As its classical counterpart, quantum information theory aims at identifying the laws and the ultimate limits governing any information process based on quantum effects.Many results in the field are phrased in terms of different resources, such as classical and quantum bits, randomness, secret bits, entanglement or non-local correlations. Results here are often transversal and find applications in different pillars. For instance, inter-conversion laws between classical and quantum bits can be used to alleviate the experimental implementation of many protocols. Another objective of the field is the development of certification methods for quantum technologies. Complex quantum systems, e.g. medium-size quantum computers or quantum simulators, are being prepared in many experimental labs. Finding efficient and scalable ways of certifying their quantum properties and correct performance is crucial for the development of quantum technologies. This necessarily includes methods for the estimation and classical simulation of complex quantum systems beyond brute-force approaches.

**Quantum foundations**. the main objective is to understand what makes quantum theory special and how it differs from classical physics, and it involves both theoretical and experimental developments. Any gap between the classical and quantum formalism is a potential resource for a new quantum information protocol. One is therefore interested in obtaining new no-go theorems for classical systems and demonstrate them in the lab. It is a powerful force to push technology forward, as it has been demonstrated by the recent “loophole-free” tests of Bell’s inequalities that not only represent seminal quantum foundation experiments, but also open new avenues for device-independent protocols and can be seen as the best-so-far sharing of high-quality entanglement between remote sites. At the same time, the concept of quantum information provides new insights to gain a better understanding of quantum physics and how it differs from other theories, including those that go beyond the quantum laws. Fundamental concepts such as causality or relativity theory change when combined with quantum phenomena.

**Decoherence**: the main challenge in any quantum information implementation is decoherence. Under its presence, quantum effects disappear, a classical explanation of the experiment becomes possible and any advantage for quantum information processing is lost. Therefore, understanding those mechanisms behind decoherence and how to mitigate their effects is a fundamental research line transversal to all pillars. The main objective is to develop the methods for the theoretical and experimental investigation of open-system dynamics. These can be used for the study of the quantum-to-classical transition. Of particular relevance is pushing the boundaries at which quantum effects can still be observed and see how to experimental prepare and maintain, in a controlled way, macroscopic systems in coherent or even entangled quantum states. This may involve various platforms, including quantum opto-mechanics. Understanding decoherence is also fundamental for the development of methods to fight against, such as error correction, dynamical decoupling, or reservoir engineering.

**Quantum information beyond quantum information technologies.** concept and tools developed for quantum information technologies find an application and provide new useful insights in other scientific disciplines. This a very broad research line, ranging from biology and thermodynamics to condensed matter or high-energy physics. In fact, quantum technologies are reaching many regimes where new theoretical developments are necessary. For example, technologies involving long distances such as quantum communications in space or very high precision measurements including atomic clocks and atom interferometry reach situations where gravity can no longer be described by Newtonian physics and relativity kicks-in. New theoretical and experimental developments will be necessary to model physics at these scales. Most of the effects can be accounted for by current theory only when systems are not entangled. However, entangled quantum clocks, photonic signals and atoms in interferometry will require deeper understandings. Including relativistic effects is not only necessary to make corrections to current technologies but also promise to lead to new technologies in the long term.

New regimes are also within reach in thermodynamic processes. Thermodynamic laws are usually phrased at the macroscopic scales including many particles where fluctuations are irrelevant. However, quantum technologies allow the study of thermodynamic effects at the quantum scale, where entanglement and coherences appear and fluctuations become relevant. Adapting the thermodynamic formalism to the quantum regime and explore the experimental implications also deserves further investigation.

Similar considerations appear when considering the presence of quantum effects in biology and life sciences A question of growing interest is to find out if biological processes exploit quantum effects such as entanglement, coherence and squeezing. For that, it is important to find out if quantum effects persist in hotter, wetter and less controlled environments. Even more relevant is to show that there are biological processes that require quantum theory to reach the efficiencies observed. These include quantum behaviour in biomolecules, energy transfer in biological systems and coherence in biological systems. Progress in quantum biology not only deepen our understanding of life but also sensing beyond the surface of biological systems promises a revolution in detection and diagnosis in healthcare.

Finally, quantum technologies are also reaching new regimes in the preparation of complex many-body systems. This allows exploring novel phases of matter from a quantum information perspective and for quantum information purposes, including the characterization of many-body systems with topological properties. It also allows for the exploration of novel platforms implementing strongly interacting quantum many-body systems, such as systems with long-range interactions. A better understanding of all these quantum many-body systems can find important implications for the design of better materials or improve our understanding of superconductivity. To reach these objectives it is also fundamental to develop quantum-inspired methods for the classical simulation of complex quantum systems.

Technological Resources

The cross-cutting activities of the quantum flagship represent and provide the technological resources needed to ensure a coherent and efficient exploitation of concepts, tools, technologies and people across the flagship. These activities include: Engineering, Control, Software, and Theory. In the following we highlight some of the key challenges in these areas.

**Engineering** will be important to improve quality, scaling, costs, etc. for quantum technologies and it will be equally important to develop a strategy to support the short- and long-term resource development. We also need to consider the importance of both engineering *of* quantum technologies and engineering *for* quantum technologies as both are necessary for the success of the quantum flagship. Engineering *for* quantum technologies, in the sense of the development of lasers, electronics, cryogenics, etc. that will enable the advancement towards markets, while engineering *of* quantum technologies addresses the more immediate challenge of developing better, more robust, scalable quantum components, devices and systems.

Key resources likely to play an important role are, for example:

* Fabrication and materials — access to advanced fabrication facilities beyond university- level capabilities. Organise/provide access to European fabrication and packaging facilities.
* Components, subsystems, systems engineering. Lasers, control systems, FPGAs.
* Verification and benchmarking to prove an application’s performance.

Many Flagship efforts require micro- and nano-fabrication, as well as packaging and dedicated microwave- and optical engineering including cryogenics and cryo-compatibility. Eventually even advanced university cleanrooms will not be able to meet requirements and we need to develop a way for the all these communities to come together here to ensure an efficient use of resources and a scalable development path for the future. There are large scale facilities such as IMEC and LETI for photonics and semiconductors as well as smaller foundries such as IPHT for superconductors, among others, but they are very fragmented, and they need the QT community to identify relevant technologies, materials etc., and try to federate competencies that already exist. This also has to be further complimented by the development of easily accessible integrated circuit libraries, for circuit elements with quantum-levels of performance and functionalities, and intermediate-scale prototyping centres for multi-wafer projects, etc., as a way to manage development costs. Similarly for packaging, e.g. of specialty chips, there is a need to bring people together from different areas, e.g. ions and integrated optics. Support is needed for all of these activities.

**Control:** The realisation of Quantum Technologies, which fully utilise the potential of quantum mechanics, still remains a major challenge due to the fragile nature of quantum states. Quantum technology requires the precise control over multiple small quantum sub-systems (e.g. atoms), but at the same time has to be capable of operating efficiently in a noisy and decoherence-inducing environment. Indeed, decoherence and the lack of robust quantum control protocols is one of the reasons that have prevented the realisation of quantum technology, namely its transition from the laboratory to the commercial market, up to now.

Therefore, there is a demand for new high-precision quantum control schemes in theory and experiment that have the capacity to outrun decoherence. These control schemes must be insensitive to experimental imperfections in the lab and especially, in the future, also to imperfections outside the lab when the quantum technology will have moved to the commercial market. The theoretical studies of new control schemes as well as the experimental development of new control schemes are key technological resources for applications in quantum information sciences, and could also be very beneficial to quantum sensors, quantum repeaters and quantum simulators.

Successful implementations of quantum technologies face the challenge to preserve the relevant nonclassical features at the level of device operation. Quantum optimal control provides toolboxes that allow one to identify the performance limits for a given device implementation, and it provides the protocols for realising device operation within those limits.

Some challenges are:

* Extend the understanding of controllability from closed to open quantum systems, in particular those with non-Markovian dynamics and from single quantum systems to ensembles
* Efficient numerical techniques for optimal control of open systems.
* Improved link to experiments, development of standardized interfaces between experiment and theory
* understanding of control complexity, in particular scaling with system size.
* Easy to use optimal control algorithms and software packages

With a focus on applications in quantum technologies, the main goal is to reach convergence between theory and application over a wide range of platforms.

Several current quantum technology platforms show a strong scaling potential. Thus in the long term, control schemes need to be made scalable. Meeting this challenge will make quantum control a basic building block of every quantum technology and ensure, at the same time, their proper functioning in a world that is only partially quantum. Qubit controls should be robust to the influences of the rest of the architecture they are placed in. Independent of a specific platform, error correction at large, for instance by toric codes, is one of the strategic long-term goals that is expected to benefit from control techniques given recent advances by randomised benchmarking. To this end, system-identification protocols matched with optimal control modules will be of importance. In short, quantum control will be the means to get the most performance out of an imperfect system and combine challenging physics at the few-qubit level with engineering at the multi-qubit level.

The long-term goal of quantum optimal control for quantum technologies is to develop a software layer enhancing the performance of quantum hardware for tasks in computing, simulation, communication, metrology and sensing beyond what is achievable by classical means, enabling the achievement of quantum supremacy.

**Software** is both a cross-cutting field as well as having a role in specific pillars like Computation and Simulation hence it is critical to address quantum software development in STR. Software can either be software that runs on quantum technologies as an application as well as classical software for low-level operation, including quantum control, of integrated quantum devices and for FPGA control. Implementing this level of software often needs to real-time capabilities and integration of different platforms. The community should develop ways to provide these, in parts by managing and coordinating a git-type library, by training programmers (often physicists) in good coding practice and by funding dedicated, open-source, open-stack, software projects that fill strategic cross-pillar and cross-platform gaps. The openness needs to be balanced with the need for developing IP portfolios. There is also a need to contribute to documentation of interfaces, standardisation and interoperability. For a successful quantum computing industry one needs to consider both the hardware and software as well as the end users.

**Theory** can be very topic-specific – but also transversal. At the heart of the whole quantum technology field are quantum states and transformations as mathematical objects. Thus, the field is built on the ideas of theorists and while some theorists work closely with experimentalists, it is very important to explore theory in its own. While there is much to be done theoretically from a “scientific Resources” perspective, there are also key cross-cutting challenges facing all application areas of the Flagship. For example, finding the right approaches to quantify information in a quantum state and understanding the computational complexity of tasks that involve quantum states. Theory can contribute to new schemes for quantum technological devices and protocols, as well as developing benchmarks for devices and systems. There is also obviously a need for close collaboration between theorist and experimentalists.

Roadmap

**Vision for 3 years**

Scientific Resource Objectives

* Further development of the concept of hybrid devices that combine at least two different systems in order to combine strengths and eliminate weaknesses
* Explore novel concepts and systems where QT can be exploited or be an advantage, e.g. in biology, chemistry and thermodynamic systems as well as across the established application areas.

Technological Resource Objectives

* Develop benchmarking suites or test-banks with which to test and showcase performance
* Miniaturisation of devices
* 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 improvement.
* Control of open quantum systems, decoherence control.
* Convergence of numerical optimal control and experimentation in many platforms, including handling of calibration uncertainties and other experimental constraints.
* Improved access and streamlining fabrication and packaging facilities.

**Vision for 6-10 years**

Scientific Resource Objectives

* The long-term objective is to continue to work towards opening up new avenues for potential growth in the filed of quantum technologies.

Technological Resource Objectives

* Develop schemes to stabilise entanglement-based networks
* Develop control for complex quantum networks
* Modular approach from simple to complicated pulses in theory, improved pulse shaping experiment.
* Implement reliable strategies for the control of mesoscopic systems.

Innovation

The quantum flagship is application-oriented and it expects to bring economic and societal benefit from quantum technologies throughout the lifetime of the programme and beyond. To achieve that goal, it is necessary that the outcomes of research meets a need in order to bring new products, which is the definition of innovation. Therefore, innovation is a central concern of the quantum flagship which involves the contribution of all stakeholders from research laboratories to industry. On the one hand research laboratories can propose new concepts and new outcomes of their work. On the other hand, industry and more generally users, having a detailed knowledge of the needs, can define specific use-cases where quantum technology-based products can bring new solutions or new functionalities that do not exist classically.

Taking a research result up to a product-ready level is a long endeavour and the laboratory demonstration is only part of the problem. As the work progresses towards the product, other considerations have to be taken into account such as reproducibility, reliability, cost, definition of standards, intellectual property management, etc. Those aspects are taken into account in the TRL scale (see general introduction). The TRL scale has proven its effectiveness for many different new technologies and therefore new products based on quantum technology should comply with that scale. This would facilitate monitoring development rates and readiness, allowing potential end-users and investors to validate the technology more easily. In this perspective, one goal is to also identify bottlenecks that can limit the transfer from research to product and propose possible solutions or improvements to this situation.

Challenges and needs for developing new products and services based on quantum technology

**Use cases and requirement specifications**

* The identification of use-cases for Quantum Technology based new products and services is an essential need to transfer research to application. QT should bring improved performances or make implementation easier. QT should even bring entirely new use-cases. Some of them have already been identified such as the measurement of magnetic fields at the nanometre scale with application to spintronics or high-density storage disks, but more are necessary to develop applications from QT.
* Identifying new use-cases occurs from discussions when a solution meets a problem. This can happen at meeting and conferences in discussions between researchers and users. Therefore, conference and workshops involving both of them are very useful. This process can be fostered by organising workshops dedicated to use-cases with specific brainstorming sessions. Several industry workshops and use-case workshops have already have been organised in the framework of the Flagship and this activity should be increased.
* Another way to identify new use-cases is to exploit software tools. This requires the identification of connections between scientific and technical capabilities (through patent or publication databases) with technical or societal needs. A preliminary test of such a platform has already been made in the framework of QSA, however, this has to be further investigated and requires a more systematic effort to be validated.
* Based on the identified use-case, requirement specifications have to defined for the new products and services.

Infrastructure and supply chain

**The Role of RTOs in new products and service development**

* There is a need for an Innovation Roadmap, similar to other fields, to guide industry. There is a large effort to set up a roadmap for photonic integration (<https://worldtechnologymappingforum.org/>). Also, the semiconductor industry has an innovation roadmap (<https://irds.ieee.org/editions>). Innovation Roadmaps should be coordinated by the EU, focussing on cooperation between Universities, RTO’s, Industry and Governments to bring new quantum technology to society as fast as possible.
* As it takes a very long time and/or large financial investment to design a product it is crucial to develop services that assist quantum technologies in identifying possible established technologies to accelerate development. The extremely long time to set up a new production facility (10 years for new SME) can also be reduced with the help of RTOs. Therefore, there is a need for RTOs to be involved in the supply chain for new quantum technology-based products.
* Create a platform to bring SME and RTO/Universities together. Actphast works well, this is a photonics H2020 project bringing platforms and universities together to support SMEs with photonics technology development. This is a Network of RTO that provides services, prototypes to SME’s. Setting up a webpage would be very useful for providing information of capabilities with information on delivery time scales, number of devices/wafers, capabilities.
* To create quantum enabled products requires repeatable and reliable production/ fabrication of quantum technology devices and system. The following actions were proposed to address this problem: Setting KPIs (Key performance indicators) for academics. Encourage working with RTO’s because they can carry out repeated fabrication. Incentivise fabrication platforms which would enable the continuation of their efforts after proof of concept projects and get involved in production.

**Identify critical infrastructure and facilities**

* Define what is needed by SME’s and start-ups to develop new QT based products. This is understood in the sense of “facilities/infrastructure made available/accessible”. Not only SMEs in QT should be addressed, but the broader field of deep-tech companies, otherwise we may miss some opportunities. The whole landscape from SME to big industry should be addressed.
* One issue is how to bridge the gap from one off production to 100 -1000 pieces. More generally the transfer from laboratory to industry (even small production) has to be addressed as well as the question of having sufficient capabilities to suddenly ramp up production if necessary. For photonic integration, this is being taken care of with some Pilot Lines (PICs4life, PIXapp, InPulse, etc).
* Develop an EU quantum computing and communication hardware infrastructure that can be used for developing services by industry, as well as bringing all stakeholders together to develop and strengthen supply chains and innovation ecosystems.
* Make access to facilities/infrastructure easier for SMEs and start-ups that may not have the means (financially or the right contacts/entry points). These facilities should also include measurement and metrology facilities and not just focus on manufacturing.
* Facilities need to advertise their capabilities: i.e. what is the state of the art in materials to see if any foundries need to be engaged.
* Networks/platforms that cover miniaturisation need to be made available and advertised to developers.
* Exploit state-of-the-art design tools such as EUROPRACTICE (http://www.europractice.com) or other Multi Project Wafer (MPW) prototyping and packaging service to European universities and industries.

**Identify critical suppliers**

* Cryogenics is currently a limiting factor for the development of QT based products and services. A group representing cryogenic industry could be created based on the various ecosystems to support the R&D activities.
* Platforms for photonic integration are now maturing and can be used for many aspects of QT. Access can be obtained directly at foundries, or through multi-project-wafer runs, for more standardised processes. The EU Pilot Lines offer a comprehensive path towards pre-production, such as InPulse (https://www.inpulse.jeppix.eu/) for indium phosphide photonics and PIXAPP (https://pixapp.eu/) for packaging.
* Quantum simulation needs to be exploited in order to maximise added value of QT at its infancy stage. Chemical process sector could be included to link up with quantum simulation.

Trained and Educated Workforce and Users

**Train personnel for working in the quantum industry**

* Using advisors/ intermediators can help translate the technology to a language industry can relate to. There are companies that provide that type of service. Identification of specialists who can act as brokers between the quantum community and facilities/ platforms can help. Those specialists need to be able to act as interpreter between the needs of the QT community and the offer from the platforms. Promote/support the presence of high-level specialists in existing facilities, who can understand needs of quantum engineer and translate them into a process/prototype.
* Develop a library of information documents such as application notes like “PICs for QT”, as has been done for other fields: http://pics4all.jeppix.eu/documents/application-notes.html, or short presentations of recent results of QT. This should be aimed at users and used around (workshops, etc) and can be disseminated widely through various channels.
* Educational workshops in partnership with industry to set up a flow of students from academia to industry.
* Train young professionals and students about entrepreneurship and prepare them to take technology to market.

**Organise workshops to raise awareness on capabilities and needs of industry**

* One should understand the needs and barriers of different sectors which would help with developing technology that is relevant and more focused to address specific problems. We should participate to industry-oriented conferences, in particular those dedicated to start-ups. Organise workshop exchange either with specific industry such the automotive industry but with a broad quantum theme or alternatively hold workshops around a specific quantum theme such as quantum for cyber-security.
* Identify the needs of industries. This could be achieved through targeted visits to companies, or by partnering for hackathons or open challenges, as well as focused workshops for industry.

Supporting and promoting the development of new products and services

The Flagship is oriented towards applications and aims at improving the transfer from research to applications. At the moment, only a few industries are involved in quantum technologies. Several directions can be investigated to try improving this situation.

**Funding and Investments**

* Special instruments are needed to support the emerging start-up scene. The nature of the start-up companies in the quantum technology is that their technologies are still mostly low TRL. This is due to the fact that Quantum Technology is an emerging field and that many ideas still need to be proven, both technically but also their market need. Because of this, start-up companies can’t find suitable funding. Most SME instruments are unsuitable because funding is provided for a much higher TRL.
* Explore means of possible EU support for large investment e.g. when facilities are required.
* List national support funds devoted to incubators for early stage SMEs. Promote EU projects that support engagement of start-ups with investors.
* Strengthen investment in European quantum technologies. Compared to the situation in the US, there are far fewer investors in QT in Europe. There are a few examples going in the right direction, but they are limited. A significant effort should be put in bringing investors and investment in the field of QT. What is important for VC’s is to show the long-term potential of a technology. It is not important if there is no return on investment within 3 years, but it is important that the potential market be very large. QT has a large potential market even if it may not be in the short term. It is therefore important to bring new things out of the box with potentially huge applications.
* Raise investor awareness. One other important aspect is to inform potential investors of the possibilities offered by QT. Most of them are not aware of the potential applications of QT. It is therefore very important to create a link between researchers and investors. All tools that can help fostering those connections are welcome. In particular, person to person meetings with decision makers are very useful to create awareness.
* Fundraising. The Flagship should promote workshops for investors to introduce them to the technology and its opportunities. Trying to develop fund raising from private funders should be a central activity of the flagship. The Flagship should address the communication barrier between investors and physicists by helping to train physicists to speak to investors.
* Quantum Consultancy. Set up a service that could make the connection between investors and quantum technology companies.

**Standardisation**

* Standardisation is an essential point to allow transfer from research to industry. The absence of standards will preclude any massive investment in the development of a technology. This question has to be addressed at the start of the technology development and can then evolve as the technology matures. An effort on standardisation has been going on at ETSI for several years in the field of quantum communications. One of the more recent initiatives comes from CEN-CENELEC which organised a dedicated meeting in Brussels in March 2019. These sorts of activities should be further pursued and become a regular activity.

**IP strategy**

* It is important to raise awareness of the QT stakeholders of the importance to protect their results. Patenting is an essential tool for that. It is part of a virtuous circle were researchers can valorise their results and make the transfer of their results to industry, which will then produce new products which generate new income and a return on investment for the researchers. An action has already been started by the European Patent Office to promote patenting and this should be continued in the next steps of the flagship.
* In addition to raising awareness, there could be a proactive action, such as an agency, to help and support academia and SMEs to file patents.
* Technology transfer significantly varies between institutions, which can be a barrier for companies. It is suggested that the Flagship should provide some guidelines to technology transfer offices to make engagement easier. Equally the Flagship should examine international best practice on dealing with technology transfer offices.

Innovation Roadmap

**Vision for 3 Years:** The identification of use-cases for QT represents and systems for identifying emerging research result are an important tool in promoting innovation. The tools for managing this and channels for promotion and dissemination should be key targets for accelerating innovation and growing ecosystems. Identifying enabling technologies developed for QT but that can be used by other fields would provide added-value to the flagship initiative. Similarly, defining and processing benchmarks and KPI’s that can evaluate the added-value of QT will be needed, along with a concerted and coherent mapping of QT to the existing EU TRL scale.

**Vision in 6-10 years:** Demonstrate and promote functionalities achieved with QT that are not achievable classically and that fulfils identified use-cases. Schemes for the evaluation QT technologies and the continued updating and improvement of benchmarks and KPIs. New enabling technologies and products that facilitate the development of QT and that find applications outside the fields of QT. Evaluate the impact of those products outside of the field of QT. Evaluate the progress of QT according to that TRL scale.

International cooperation

Europe has world-leading researchers in most domains of Quantum Technologies but it would be unrealistic to maintain such a strong position in isolation. To further strengthen Europe’s position, it is crucial to (1) foster international scientific and education cooperation, in a framework ensuring that this is a winning partnership for Europe, avoiding brain, ideas and IP drain, and (2) to support communication and coordination between European academic and research organisations and their top-level counterparts outside Europe.

QT a major disruptive sector calling for a worldwide research and innovation

Quantum technologies are one of the most disruptive R&D sectors since they might be a game-changer for the entire information and data value chain from sensing, to communication, sorting, simulating, predicting and computing.

The second quantum revolution is emerging from decades of major discoveries in quantum mechanics. This basic research activity is developing best in an open research spirit based on international collaborations.

The second quantum revolution is now entering into a new phase of technological developments. However, the key characteristic of the present technological developments is that they are still strongly “entangled” with fundamental research since the engineering race is launched at a very low maturity level while major conceptual issues are still unsolved. Even if at the international level the efforts to develop the quantum technologies are considerable, in many cases, the race might be closer to a marathon then to a sprint. The required conceptual and technological breakthroughs are calling for a worldwide research and innovation effort.

Quantum technologies are developing fast through open research and a global, public/private, cross-community efforts. The exchange of ideas in this exploratory research and development is the source of the present development of the field.

A clear framework to benefit from international collaboration

Europe has world-leading researchers in most domains of Quantum Technologies but its competitors such as China, US, Canada, Japan or Australia are strong and are massively investing to develop quantum technologies. It would be difficult or even unrealistic to maintain such a strong position in isolation. Up to now, collaboration and open exchange of ideas with leading researchers all around the world has contributed to build the European leadership. Isolating Europe or putting ill-suited barriers between Europeans and their international collaborators would in fact slow down Europe and weaken its positions.

At the same time, the disruptive potential of QT may give a huge advantage to future owners of quantum technologies and applications and thus Europe should be agile in the competition for the creation of economic value in order to protect its main interests. Quantum technologies can also raise issues of sovereignty that can change the reasoning about international collaborations. Therefore, it is crucial to foster international scientific cooperation, in a framework that ensures that this is a winning partnership for Europe, avoiding brain, ideas and IP drain.

**Preparing Europe for the international competition**

As far as brain drain is concerned, the first key remains to provide an attractive environment in Europe for key researchers and start-ups to be able to develop their ideas and activities. Putting this back in the global picture building a very competitive and attractive European ecosystem in quantum technologies is the best way to prepare Europe for the international competition.

In particular, it has been made clear[[1]](#footnote-1) that reaping the benefits of the second quantum revolution requires a consistent strategy not only in research and development, but also in 4 key areas:

* Education and training both for researchers, technology developers, and for future users
* Technology transfer and start-up support to stimulate economic value creation
* Standards and regulations which are efficient tools in international competition
* Public procurements and more generally development of use cases and stimulation of early-adopters in Europe to accelerate the development and dissemination of quantum technologies

With these assets in hand, Europe can be well prepared to face international competition and to derive the best benefit from the cooperation it will set up.

Two additional issues need to be addressed: the IP and innovation protection policy and the cooperation policy in terms of regions and countries. The IP protection is a key issue but due to its complexity and its possible political dimension, it will be treated in a separate chapter. A first strategy could be to minimise the IP issues by collaborating first on basic research or general issues for which the main deliverable will be open publication. As far the foreign affairs dimension of this topic of international collaborations is concerned, this is mainly a political issue treated at the commission and EU countries government level. In the recent EU call for a CSA on international collaborations, three countries have been specifically targeted: US, Canada and Japan.

**Cooperation in research and innovation: complementarity and critical mass**

The overall criteria for an international cooperation in research and innovation is that Europe should benefit at least as much as its partner from the international cooperation within the project.

Practically, this corresponds to cases where:

* The expertise of partners complements each other in such a way that the European partner would not be able to pursue the same objectives with the same ambition and/or at the same speed without the establishment of the international cooperation.
* The expertise of partners is of similar levels, and combining forces is likely to lead to the critical mass needed to cope with the targeted challenges. However, this is more prone to follow-on competition and should be treated carefully. The partner that is faster in a successive phase, will tend to benefit from cooperation and then run alone in competition. For example, this is the case if EU researchers are stronger at lower TRL and other non-EU researchers are faster in creating up start-ups.

In such cases, it is likely that part of the created IP would not have been obtained at all, or not in the same timescale, without setting up the international cooperation.

The way suggested to implement consistently these criteria is the following:

First, one is to determine - prior to call for projects - the scientific and technological areas where collaboration with countries outside Europe is a winning case and to restrict the call for international collaborations to this list of topics. As this approach may be too slow for some research areas and preclude the establishment of a specific and very fruitful collaboration, either on a specific topic, or with a specific international group, one could combine it with an open call with potentially different (stricter) evaluation criteria.

Then one is to determine, for each given project, if the proposed collaboration is beneficial to Europe. Indeed, scientists and their peers are well placed to analyse the complementarity or the critical mass effect of the international partners. Thus, the evaluators would then assess – project-by-project and on the basis of the case made by the proposers - the need, relevance, and win-win scheme of the international cooperation. This will lead to an integration of “mission critical” individuals, rather than funding programs.

International collaborations in education and training

The overall criteria to develop international collaborations in education and training should be the same as in research activities: Europe should benefit at least as much as its partner from the international cooperation. Therefore, either European students can learn something abroad that they cannot learn in Europe, or European institutes attract the best talent from abroad to be educated and later work in Europe (a reverse brain-drain). As relevant activities may include joint education concepts, joint courses, joint PhDs, professor exchanges… the primary indicator of success is enrolling the best students in the program. In term of evaluation criteria, this means that a lot of emphasis should be put on the visibility to be achieved by the program to be implemented.

The collaboration for training and education could be a way to develop common ‘language’ and cultures such as best practices which are a determinant to build fruitful cooperation.

The collaboration in large public communication and engagement can also be the best way to maximise the public awareness about quantum technologies similarly to what is done in the large-scale international collaborations such as space, astrophysics, particle physics and fusion energy.

**Implementation – strategy sharing, exchanges of best practices, identification of use-cases**

A successful international cooperation builds up over a strong mutual understanding, and, in the rapidly changing and challenging field of quantum technologies, there is a strong rationale to share views on best strategy and practices with high-level counterparts from governmental organisation, academics and industry (at least USA and Japan). Also, there are benefits for all players to set up at the earliest convenience the necessary working groups to define global standards for QT based products/devices. Practically, this may be pursued through specific - bilateral or trilateral - workshops gathering high-level representatives from research agencies, research institutions, government organisations and industrials active in quantum technologies.

Setting up the framework for relevant research collaborations may specifically benefit from such strategic workshops. Part of this activity is supported by the international cooperation task proposed in the QFLAG CSA. The research workshops could also participate to part of the objectives here targeted, at the level of broader research communities.

Use-cases and early adopters can be seen as one of the possible strategic discussions with key international partners. Indeed, high-tech domains such as forefront research, space exploration or health, energy and environment issues are already fields of strong international collaborations with some specific countries. Those fields could also be interesting domains to develop early applications of quantum technologies within the existing collaborations.

Addressing the IP issue: Making Europe stronger to benefit from an open world

**The delicate equilibrium between IP protection, free trade, and open research & innovation**

Quantum technologies have a huge potential of innovation which may revolutionise the information economy, shaking all businesses and disrupt the technological context of key elements of sovereignty. The mastery of IP issues is thus strategic both at the economical level, and in some cases, at the sovereignty level. These two issues should guide the partnership policy.

The IP protection calls for a global policy throughout its entire life from the creation of new IP to its licensing and transformation into new businesses including its future when those businesses evolve. Indeed, the simplest way to capture IP is to buy the company owning the IP or a license to exploit it. Moreover, large companies are international and are implanted in different countries either directly or through subsidiaries or joint ventures. Thus, the reflection about a consistent IP protection policy should not only evaluate the pros and cons of open innovation versus restricted collaborations, but it should also consider the targeted equilibrium between protectionism and free trade.

None of these issues are specific to quantum technologies. Nevertheless, the huge impact foreseen from quantum technologies make them, maybe, a more burning issue.

Also, there is need to raise awareness about “immaterial IP” with European academics: Researchers are usually driven in thinking that the subject of their research is the key container of all the IP they are generating. This is obviously true. But, other minor aspects, such as the way everyday problems are solved to actually e.g. make that experiment work or this measurement effective are not regarded as important and sometimes leaked as side comments in discussion/presentations/panels: such apparently minor details could actually make the difference between a successful product and an R&D disaster at a later stage.

The only way of protecting this is through self-discipline: whilst it is important to cooperate, it is also important to avoid lingering on aspects that aren't in the scope and are not relevant to the cooperation subject. Strengthening IP protection within the flagship remains an important requirement and a daily task.

**A specific protection, when sovereignty is involved**

The quantum technologies may impact areas of sovereignty for Europe or for some European countries. Sovereignty may lead to a country dependent policy and to specific development[[2]](#footnote-2) and protection[[3]](#footnote-3) programs. Many European countries have such schemes.

This question of sovereignty should be addressed in each country, probably relying on a permanent exchange of information between the community and their government representative in order to monitor and analyse the progress and evolution of quantum technologies. A joint vision of this question at the European level would help to smoothly manage it in the flagship.

**Favour the strengthening of European research, innovation and business**

As far as research, innovation or economy are concerned it is important to recall that barriers have often proved to be counterproductive. Indeed, barriers work both ways and, if they provide protection, they also reduce the flow of information and opportunities that feed Europe and boost its economy, its research and innovation dynamics. The best option appears to keep the system open, and to obtain the needed protection, not through barriers and limitations, but through the strengthening of the European research, innovation and business ecosystem. A soft power strategy.

The first point is to have a clear and strong IP policy. Taking patents and other relevant IP protection measures should be strongly encouraged or required in EU or MS grants, and by relevant institutions[[4]](#footnote-4). In the framework of research projects resulting from calls opened to international cooperation, consortium agreement should ensure equilibrated rights of exploitation and use of the created IP, so that EU can benefit from each project. Patents are good, but a coherent portfolio of patents would be more effective. EU could help in connecting and exploiting patents from different projects as part of a coherent portfolio[[5]](#footnote-5). Finally licencing is the path towards business creation and licencing should be carefully done in order to ensure the best possible IP management. Sharing good practices and issuing guideline could be part of the setting up of relevant IP protection. Also, joint agreements between academics, SMEs and larger companies could be a way to help the filing of patents and fund their support throughout their life-cycle.

A second point, providing an immense soft power and implicitly keeping Europe at the most advanced level with benefit to business, is for Europe to lead the (global) international working groups defining the needed technical standards for practical implementation (as it was back at the beginning of mobile communication). This will prevent the largest players from developing their own and force the other players to catch up. At the same time, it will provide the necessary technical stability that European industrial players would like to see as one of the conditions to release big investments and provide a levelled playing field as a basis for fair competition.

Other actions, beyond research and research management, are needed, and are cited below. They correspond to policies already implemented by EU and member states, but maybe not to the desirable extent. These actions are part of a successful innovation policy, which cannot rely only on research and research management, but also depends on a consistent set of measures and an overall favourable context.

One point could be to (further) foster the emergence of strong European investment funds able to support the early stages of start-up growth, and their transformation into mid-size companies. One way, already implemented in some countries and planned on a European level as part of the European Innovation Council (EIC), is to keep an eye on progress with the possibility to act on the evolution of start-ups and companies, which would require direct government investment in their capital. This call in favour of member states or the EU, as well as active investment funds, does not contradict the desirable dynamics of private EU-based investment funds.

A second one could be to make Europe more attractive to avoid the displacement of innovative industries to other countries and even to attract foreign companies to Europe. In particular, EU and member states could further support the emergence of strong local QT innovation ecosystems, where companies will find a combination of public research (University, RTO…), industry, high quality workforce and platforms to pursue their development.

Following the leading role in coordinating the global definition of standards and the investment in facilities that have already been made, Europe could focus one or more (better more) of such local ecosystems as a "go to place" for test, verification and validation of products based on quantum technology.

Gender Equality

Quantum physics and technologies represents a special case in terms of gender equality. This is because

1. Women are in clear minority in the quantum technologies field where the number of women in quantum physics and technologies is lower than average in STEM and
2. This is a potentially high-growth area that will have a significant effect on the demographic of scientists in the EU.

Overall women represent 20% of the physics graduates and doctorates[[6]](#footnote-6) and 13% of the engineers[[7]](#footnote-7) in STEM. This is a problem that needs to be fully assessed, for which statistics focused on the quantum physics and technologies fields are needed that give a better reflection of the ecosystem in a quantitative and qualitative way, alongside a battery of measures directed to correct the imbalance. The quantum community needs (additional) resources, including dedicated funding allocated to gender equality, and a dedicated CSAs for gender equity in the quantum community.

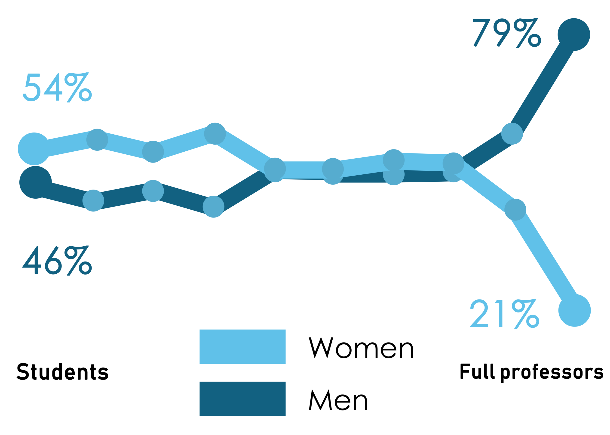
Despite the progress that has been made in getting women into science at the university level, there remains a challenge to ensure the promotion of women to senior positions, increase their representation as conference presenters, chairs, PI of important grants, and, in general, their equal treatment. **The impact of the participation of women is overall positive, contributing to increasing the quality, societal relevance and competitiveness of research and innovation**[[8]](#footnote-8). Furthermore, according to a new research from the McKinsey Global Institute, **to the improvement of the global economy**, stating that by advancing women’s equality, $12 trillion could be added to global GDP by 2025[[9]](#footnote-9). It is thus **that the work on gender equality is of such significant strategic importance that it should have a place alongside science, innovation, industry, education** etc. in the Strategic Research Agenda.

Equality, or if preferred, Equity, and diversity issues are wide-ranging and include age, living location, gender, gender orientation, sexuality, religion, indigenous status, cultural and linguistic background, race, disability, mental and physical health, pregnancy, parenting, and other responsibilities related to care of dependents. While the strategy should initially focus on the challenges related to gender, solutions and the implicit change towards a more diverse, tolerant culture could also have a more positive impact on these other areas.

The leaky pipe challenge

In the overall realm of STEM careers, which include all disciplines within science, technology, engineering and mathematics, there has been progress in getting women into science; The share of women at the top level of an academic career rose from 18 % in 2007 to 21 % in 2013. The share of women heads of higher education institutions rose from 15.5 % in 2010 to 20 % in 2014[[10]](#footnote-10). Please note that these numbers are across STEM, and that for the quantum technologies field evidence suggest that these are even lower. Despite this, there remains a challenge to ensure the promotion of women to senior positions, increase their representation as conference presenters, chairs, PI of important grants, and, in general, their equal treatment. Many countries, institutions and national research initiatives have developed programmes to help support women in Science, Technology, Engineering and Maths (STEM), areas which have a good overlap with the diverse fields involved in Quantum Technologies. In industry, we see similar challenges.

One of the most marked problems facing gender equality in quantum science, and STEM in general, is what is called the leaky pipeline. We seem to be able to reach reasonable numbers of female undergraduate students but as their career progresses through post-graduate studies and towards full professorships, the ratio tips significantly towards men. The graphic[[11]](#footnote-11) on the left is for all sciences (in Spain). However, in QT we are generally struggling to even come close to 50% for the undergraduate stage.



*Figure adapted from* [*http://www.ciencia.gob.es*](http://www.ciencia.gob.es)

A different way to see this problem is through the vertical segregation that occurs across sectors for women, regardless of the numbers of women at entry level. This is established by the imbalance between women and men in leadership categories (occupational hierarchies) where men dominate leadership categories while women are concentrated in non-management roles[[12]](#footnote-12)[[13]](#footnote-13).

Approach to gender equality in the Quantum Flagship

The current CSA underlying the Quantum Flagship does not have the budget to create and implement a full strategy to help solve the gender inequality that the quantum technologies field faces. However, it has created a working group dedicated to this matter; the Gender Equality Working Group (GE-WG) that aims to provide the structure and support to a network of female and male members of the Quantum Technologies community. This WG has identified the following working areas:

**Statistics around gender distribution in the community and at events**

There are several reports[[14]](#footnote-14) available that describe gender distribution in research and innovation or science and technology in different geographical areas. There is though, little information centred specifically on the quantum technologies arena. While many people perceive that the number of women in this field is low, the community lacks numbers based on facts. This information is key to present the challenge of gender inequality in an unbiased way so that measures can be put in place to correct the situation and to be able to measure the impact of the actions that are set in place to correct the gender imbalance.

**Identification and organisation of activities/ actions to improve gender equality**

Many countries, institutions and national research initiatives have programmes to help support women in Science, Technology, Engineering and Mathematics (STEM), which has a good overlap with the diverse fields involved in Quantum Technologies. However, we need additional actions targeting the Quantum Technology community, where the statistical numbers collected so far indicate a larger gender inequality. These actions include unconscious bias training, support programmes and events to involve the community at large in acknowledging and tackling gender inequality, ensuring that the approach has cross-gender, cross-generational reach and involves internal and external experts in science, gender and technology policies. This will bring content and perspective to the challenge, and will especially become a useful tool and insight provider for the quantum community as well as the European Commission in order to work towards gender balance and inclusivity.

**Raise awareness and especially raise visibility of female scientists**

The visibility of women scientists is important for two aspects: because it is only fair that professionals with the same accomplishments get the same recognition and visibility and because it is often the case that women are able to attract more female talent to their teams than their male colleagues. One reason for the low number of women in leadership positions, as speakers in scientific meetings, as experts on boards or interviewed by the media, is that women are less visible than men. The quantum community needs to make an effort to increase the participation of women in visible positions. Part of the community is already aware of the importance of including women in their structures and events. Unfortunately, given the low visibility of the female community overall, only a few women are being constantly requested. This leads to a saturation of the agendas of these few women. It is thus important to have a database that includes female scientists and to make it widely available, so that organisers of events, boards or media requests, are aware of this pool of talent. At the same time, having women of the community more visible will help to influence young and early-career female students in the process of deciding their career paths and to pursue a career in quantum technologies.

**Create a networking and mentoring structure**

It is important to create a networking structure for the community to get together on gender issues. It is necessary to have this structure open and reachable especially to the early-career members of the community with the involvement of the members in more senior positions. Mentors and role models play an important role in career path options, and as mentioned before, women often attract other women to the field, so that systems in which we can bring together and encourage mentoring schemes can be effective tools for the career advancement of women. We would also note that men mentoring women very effective. This is mainly due for two reasons; men typically have better networks and the eye-opening effect that mentoring has on the male mentors in terms of the barriers that their female mentees face. Of importance here is to determine the right mentoring and networking schemes that are best suited for the quantum community, as different models have different impacts and benefits[[15]](#footnote-15).

Conclusion

Gender equality is key to the quantum community not only for social fairness but because it has been proven that it has positive impact in productivity and innovation. The community perception is that in quantum technologies the gender imbalance is particularly large. However, we need to acquire suitable statistics to have a clear picture of the landscape in the field, as well as a suite of actions to address the gender imbalance. Actions have to be carried forward and structures to be put in place to create an ecosystem that enables the number and visibility of female scientists to increase across all levels of the value chain of quantum technologies, from the Quantum Flagship itself to the related industries, and to the future workforce of the field (STEM undergraduates). For that, we need funding in form of dedicated CSAs.

Gender Equality Roadmap

**3 year Vision:**

* **Statistics and key performance indicators (KPI) methodology in place**: procedure to collect and monitor gender-related information that will allow us to **understand the actual situation** in terms of gender equity and existing ecosystem as well as **measure the impact of the measures** that the Quantum Flagship is taking
* **Charter for gender equality 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.
* **Special dissemination channels and materials:** to increase the presence of female quantum technology researchers at conferences as attendees as well as engage the female scientific community in quantum technologies. The Quantum Flagship should collaborate with **forums, networks and associations** directed to women scientists and engineers, in academia and the industry to better leverage these efforts.
* **Unconscious bias training program** for the quantum community: biases affect everyone, regardless of their own personal characteristics; signs of these behaviours in science are everywhere, starting in schools and continuing through all levels of the career ladder. This translates into women in science earning less, being less likely to be promoted or receive letters of recommendation, and more likely to quit altogether[[16]](#footnote-16). 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. Training material and events will be collected, publicised, and made available to the community. The training must be carried out by **professionals with expertise** in gender diversity that can engage with the quantum community at all levels of seniority. This is important to help women progress in their careers and move to leadership positions, and to create the right ecosystem that promotes everyone’s careers.
* **Creation of outreach programs**: it is key to increase the number of potential professionals in quantum technologies, and for that, we need to increase the number of female students in STEM careers, especially those that show a more direct link to QTs (e.g. physics, engineering and mathematics). For that, we need **outreach programs directed to female STEM undergraduates, to promote and increase visibility of professional opportunities that QTs provide to them**.

**6-10 year vision:**

* **Gender equity in conferences**: through the implementation of the conference charter and the promotion of the visibility of women in quantum, Quantum Flagship related conferences will reach **full gender equality in their speaker and moderators panels**.
* **A mentoring system in place**: the Quantum Flagship needs to have mentoring structures and systems in place specifically targeted and adapted to the quantum technologies community. Working together with experts from organisations such as WISE (Women in Science and Engineering), and learning from initiatives such as <http://www.jamaissanselles.fr/>, the **Quantum Flagship needs to set up a mentoring system** that provides a support to the community, especially to the career promotion of women.
* **Unconscious bias training**: The aim is to have all members of the Quantum Flagship projects undergo unconscious bias training at the beginning of the project as a project condition, and the PI and Co-PI having demonstrated that they have undergone the training as a condition for the project proposal to be considered for funding.
* **Monitor the KPIs of the gender equality actions**: follow the gender equality situation of the quantum community monitoring the KPIs and underlying methodologies.
* **Gender equality in the Quantum Flagship**: to reach full gender equality in leading roles in the Quantum Flagship structures as well as in its membership
* **Increase the number of women in QF projects**: Women in WP leadership positions should be at least **30%** of the total positions in projects within the Quantum Flagship
* **Increase the number of female PhD students in QTs**: an increase of at least 50% in the number of PhD students in QT-related programs to be women.
* **Expansion of outreach programs** directed to female STEM undergraduates: ensure that outreach programs directed to female STEM students are being rolled out across Europe.
* **Impact assessment of the gender equality actions**: in terms of the increased presence of women in the quantum technologies community and of the changes in the ecosystem and its impact in the research and innovation of the Quantum Flagship.

Education and Training

If Europe strives to be a leading force in the field of Quantum Technologies (QT), the need for a quantum workforce and a well-informed society with knowledge and attitudes towards the acceptance of QT is imminent. In order to provide a solid long-term, sustainable implementation and progress of QT, a strong support of European Quantum Education is necessary. The challenge of an immense scaling-up in training and education while increasing interdisciplinarity and drawing acute attention to current and future corporate and societal needs can only be achieved with a comprehensive and coordinated effort. This endeavour has to establish an ecosystem bringing together all involved stakeholders.

Current Status

While quantum physics today is included in all university physics curricula and touched upon in high school curricula in some, but not all European countries[[17]](#footnote-17), this does not satisfy the needs for a workforce ready to bring quantum technologies into engineering applications. In order to move the emerging field of quantum technologies closer to the needs of industry and general society, a modern and dedicated quantum education is needed throughout Europe, leading to quantum awareness and literacy for a broader range for schools, university students and the workforce than today.

To address the challenge, the Quantum Community Network (QCN) has joined forces with leading physics education experts. As a result, a new community gathering educators, academics, communicators and industry representatives engaged in Quantum Education at all levels is emerging. This summary presents the first outcomes: envisioned pillars of the strategic education agenda within the flagship build upon the community needs (Oberkochen paper[[18]](#footnote-18)) as well as first recommendation for the short- and long-term actions.

#### Advances in quantum education and educational research needed to meet future challenges

The most urgent challenge consists in developing and evaluating effective training and educational modules for a variety of learners in the areas that traditionally do not get in touch with quantum physics (e. g. engineering, computer science, mathematics). The conventional formal introduction to quantum physics, based on the concepts of 20th-century physics, will not meet the needs of these audiences. An educational approach conveying “quantum awareness” and motivation is needed, shifting the emphasis to more conceptual and intuitive understanding. This is particularly pertinent in view of the paradigm shift from quantum theory as a theory of microscopic matter to quantum theory as a framework for technological applications and information processing. This paradigmatic change in teaching and learning of quantum physics merges decades of Physics Education Research[[19]](#footnote-19) and recently developed ICT-based approaches incorporating visualisations, simulations, education experiments, visitor’s labs,and games. Research in physics education documents that a conceptual and intuitive approach will also enhance the quantum education of physics students.

A conceptual approach to quantum teaching also ensures a low barrier of entry to the core concepts of quantum physics as well as the motivation for engaging with the more mathematical aspects of the topics. The emphasis on the conceptual and intuition-based aspects of quantum physics will also foster large-scale quantum awareness through implementation into the secondary (and eventually primary) school system and public engagement initiatives. Such a new approach would also be interdisciplinary friendly and different segments of society could cross-reference with their own field of expertise. Such a familiarisation with quantum concepts is a key for a mindful and non-prejudicial interaction with quantum devices on a large scale. Thus, a conceptual approach based on educational research will provide a valuable addition to the existing expert training in physics.

A corresponding education and training program can be based on **three interconnected pillars** addressing different audiences:

1. **University education.** In this pillar the main target is a modern quantum curriculum for future quantum technology workforce. By joining forces across Europe for building quality-controlled teaching resources and methods based on empirical educational research, quantum education at the university level can be greatly enhanced. Target groups in this pillar are students at the Associate Degree and Bachelor, Master and PhD levels in Quantum Science and Technology, related topics such as Physics, Mathematics, Engineering, Computer Science and Chemistry, pre-service teachers in these topics, as well as academic staff and decision makers (ministries, university and faculty boards).
2. **Training of industry workforce.** The main issue for industry is to develop concepts for getting the current workforce up to the level of current quantum technology. This involves decision makers in industry (CEOs, CTOs, SME organisations) as well as the members of the current workforce themselves, which need special training courses to keep up with the progress of the second quantum revolution.
3. **High school education.** In high school education, two targets need to be addressed: building general quantum awareness for all citizens and quantum literacy for the future quantum scientist and engineers. This pillar will address *in-service teachers* and *high school students* through new quantum curricula recommendations and teaching strategies, based on educational research, as well as *decision makers* in this sector (ministries of education, school organisations, e.g. for building a quantum curriculum).

Planned measures

For the coordination of the efforts there is an immediate need for an Education Coordination and Support Action to (1) perform an extensive mapping of current and future requirements for education and training, (2) define standards for implementing appropriate educational strategies, (3) host existing and newly developed teaching materials and resources within a repository, (4) develop strategies for scaling up advanced quantum technology training programs (e.g. QuTech Academy), (5) establish a network between science and industry to exchange ideas, needs, and human resources (e. g. in the form of student internships). Moreover, there is a need to establish a European Quantum Education Community Network, with a structure similar to the Quantum Community Network (QCN) that comprises representatives of the member states, to help coordinating the education activities and strategies between the Education Coordination and Support Action and the national initiatives.

**Vision in 3 years**

* Consolidated the needs and challenges of Quantum Education on the (i) university and (ii) high school education level and of (iii) the quantum industry and formulated measures how these needs can be met (Education CSA).
* Built a repository of scientific literature and education studies, material and resources, documenting and classifying learning activities and methods as well as listing key partners for QT education in Europe. (Education CSA)
* Researched the needs and feasibility of a QT curriculum for all levels, resulting in a proposed QT curriculum description and example teaching material, teaching methods and evaluation concepts.
* formulated standards for QT competencies at different competence levels. Since quantum engineering is an emerging discipline, there is no generally accepted definition of the competencies to be acquired. The Quantum Competence Framework (QCF) will be modelled after the example of the European Digital Competence Framework (DigComp). It will be empirically assessed and serve as a guideline for newly developed education programs. (Education CSA).
* Built a network platform and established regular national and international meetings between the QT research community, education research community, QT industry, educational authorities and further key partners
* Developed pilot programs for a Master degree in Quantum Technology and Quantum engineering for Scientists and Engineers, with student training in companies in each EU country, coming from different backgrounds (physicists, engineers, computer scientists)
* Specifically addressed the needs of member states, which have not yet a strong QT research community and/or industry of the 2nd quantum revolution to
* Develop and evaluate formal and informal quality learning resources made accessible online at no cost (e.g. MOOCs, Jupyter Notebooks/Labs, Virtual Quantum Lab, gamification, QT demonstrators, apps…) using the most up-to-date online and virtual training technologies.
* Provide hands-on learning experience that is reproducible/scalable at low cost by developing laboratory experiments based on the most recent results of research in QT and physics education.
* Develop exchange programmes (e.g. COST action, Erasmus Mundus+, mobility grants...) to foster local expertise and support regional education clusters in university and high school education (teachers and students) and job rotation programs and secondments to academia for existing work-force to access unique QT infrastructure and expand knowledge base.
* Set-up joint summer schools for High School students involving quantum-physics laboratories in different European universities.
* Develop and implement intense training programs for Quantum Education (e.g. summer/winter schools) for university students, PhD students and industry workforce.
* Raised quantum awareness across all member states in Europe through short-term, immediate actions to demonstrate societal benefits of QT (e. g. via public experiments on quantum technologies or the presence in traditional and social media).

**Vision in 6-10 years**

* A pilot program to implement a reformed approach of both formal and informal QT learning in selected member states for the (i) university and (ii) high school education level and (iii) the quantum industry, including
  + A certificate system in Quantum Technology based on the empirically evaluated QCF standards.
  + Pan-European launch of interdisciplinary QT-Master courses in Quantum Engineering containing a component of leadership, industry and entrepreneurial skills training, based on the evaluation results of the pilot program.
* Established self-sustained pan-European education programmes in quantum technology
* Implemented innovative research-based curricula for the (i) university and (ii) high school education level and (iii) the quantum industry that will
  + Include frontier science and real-life scientific challenges
  + Build on a combination of formal, rigorous education in quantum science and technology and conceptual, intuition-based learning approaches, including gamification and approaches based on virtual reality methods.
  + Integrate school activities and extracurricular activities embedded in national initiatives (e.g. exhibitions, science festivals, student laboratories…)
  + Be tested and evaluated in real teaching situations in teachers’ education.
* An educational approach for secondary schools and teacher education based on conceptual and intuitive understanding, including research-based quantum curricula recommendations and empirically evaluated teaching strategies for secondary schools and teacher education
* Joint international graduate schools for learners from different areas with opportunity for students to gather international experience (Marie Curie ITN/ETN)
* University activities for high school students (Quantum Master Classes) Involvement of decision makers through e.g. educational advisory boards, job-shadowing, grey literature/briefings/recommendations
* Network platform and regular international meetings systematically extended to SMEs
* Transcending support across all measures to address inclusiveness in terms of diversity in internal (e.g. gender, ethnicity), external (e.g. parental status, work experience) and organisational dimension (e.g. work location, seniority).
* Recommendations for education at primary level in preparation for QT education at secondary level
* A satisfactory level of awareness on the benefits QTs bring to society.

Conclusion

In summary, the creation of a learning ecosystem embracing the concepts of quantum physics at all levels ranging from school up to the working environment is required for the quantum-ready workforce to emerge. The envisioned strategy is an educational approach based on a combination of conceptual understanding and formal training that starts with the societal and company needs and builds up into a quality controlled educational concept.

1. Such as the Quantum Technologies Flagship Final Report written by the High-Level Steering Committee appointed by the European Commission (report delivered on 28 June 2017). [↑](#footnote-ref-1)
2. e.g. targeted research and development programs could be financed at European or members state level. [↑](#footnote-ref-2)
3. e.g. a legislation allowing states to prohibit or frame the acquisition of a company active in a strategic field by a foreign investor could be generalised. Many European countries have such scheme. [↑](#footnote-ref-3)
4. In some cases a conscious decision could also be taken *not* to file a patent, in order to keep crucial knowledge secret. In these cases, Non-Disclosure Agreements need to be put in place. [↑](#footnote-ref-4)
5. This might be specifically useful when patents are filed by small, even if highly innovative, research institutions since their patent portfolio might be too small to ensure the best possible valorisation dynamics. [↑](#footnote-ref-5)
6. Women in Physics and Astronomy, 2019, American Institute of Physics [↑](#footnote-ref-6)
7. Roberta Rincon, Ph.D., Manager of Research, SWE <https://alltogether.swe.org/2018/09/swe-research-update-women-in-engineering-by-the-numbers/> [↑](#footnote-ref-7)
8. <http://www.ciencia.gob.es/stfls/MICINN/Organismos_Intermedios/FICHEROS/Guidance_to_facilitate_the_implementation.pdf> [↑](#footnote-ref-8)
9. https://www.mckinsey.com/mgi/overview/in-the-news/the-economic-benefits-of-gender-parity [↑](#footnote-ref-9)
10. https://eige.europa.eu/sites/default/files/mh0716096enn.pdf [↑](#footnote-ref-10)
11. Adapted from <http://www.ciencia.gob.es> (Spanish female scientists report 2015) [↑](#footnote-ref-11)
12. Gender segregation in the workplace and its impact on women's economic equality, Commonwealth of Australia 2017 ISBN 978-1-76010-568-6 [↑](#footnote-ref-12)
13. Women in the Workplace, McKinsey& Co 2018 [↑](#footnote-ref-13)
14. Reports of EFFORTI ([www.efforti.eu](http://www.efforti.eu))

    <http://uis.unesco.org/sites/default/files/documents/fs51-women-in-science-2018-en.pdf> <https://ec.europa.eu/eurostat/web/products-eurostat-news/-/EDN-20190211-1> [↑](#footnote-ref-14)
15. Women and leadership: the role of mentoring and networking, Schipani at el. 2008 ALSB National Proceedings [↑](#footnote-ref-15)
16. K Dutt et al, Nat. Geosci., 2016, 9, 805 (DOI: 10.1038/ngeo2819) [↑](#footnote-ref-16)
17. Stadermann, H. K. E., van den Berg, E., Goedhart, M. J., Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic. Phys. Rev. Phys. Educ. Res. 15, 010130 (2019). [↑](#footnote-ref-17)
18. Education / Training and networking section from Supporting QT beyond H2020 summarizing the Quantum Flagship community meeting in Oberkochen (Germany) on 19. 04. 2018, https://qt.eu/engage/resources/ [↑](#footnote-ref-18)
19. Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A. & van Joolingen, W. R. Insights into teaching quantum mechanics in secondary and lower undergraduate education. Physical Review Physics Education Research 13, (2017). [↑](#footnote-ref-19)